Maximising the Effectiveness of Aerial 1080 Control of Possums (*Trichosurus vulpecula*)

A thesis
submitted in partial fulfilment
of the requirements for the Degree of
Doctor of Philosophy

At
Lincoln University

By

David R. Morgan

Lincoln University
2004

Abstract of a thesis submitted in partial fulfilment of the
requirements for the Degree of Ph.D.

Maximising the Effectiveness of Aerial 1080 Control of Possums (*Trichosurus vulpecula*)

by D.R. Morgan

Aerial control using 1080 (sodium monofluoroacetate) baits is widely used in New Zealand for the control of introduced brushtail possums (*Trichosurus vulpecula*), with the aim of protecting national conservation and agricultural values from these damaging pests. This thesis integrates research, completed over 25 years, that was motivated by growing recognition in the 1970s of the extent of possum impacts and the need to improve the effectiveness and efficiency of the control operation.

Field research assessed the palatability of three types of cereal-based pellet baits and carrot baits in different regions, habitat types and seasons. Palatability was assessed by the consumption of the different bait types presented independently of each other on 15-30 plots, with rotation of bait types at plots on successive nights to provide equal exposure to each bait type. There was regional variation in possums' bait preferences, possibly reflecting genotypic differences, whereas seasonal variation was less evident. Carrot bait was preferred or equally preferred to cereal bait in 14 out of 20 field trials.

The proportion of possums eating baits was then investigated by, firstly, developing a technique for tracing bait acceptance using rhodamine B, a UV-fluorescent dye. In four field trials, more than 95% of possums accepted three types of dye-marked bait, eliminating bait refusal as a major reason for low kills in winter control operations. In a fifth trial, conducted in summer, only 68% of possums accepted bait suggesting that seasonal availability of favoured foods may influence bait acceptance.

Since possums must encounter baits before deciding whether to eat them, field studies were undertaken to assess the coverage achieved in normal aerial baiting operations. Large gaps, up to 400 m in width, were often found between baiting swaths; these could allow some possums to survive. A controlled field experiment, using acceptance of rhodamine-dyed bait as a measure of effectiveness, showed that bait distribution was least accurate where flight

paths were not marked. Where gaps of 100 m between flight paths were deliberately created, bait acceptance was slower and less than where coverage was complete. Sowing baits at 3 kg/ha was as effective as at 10 kg/ha, indicating the potential for substantially reducing operational costs by using machinery capable of faultlessly distributing baits at low rates. Navigational guidance systems were evaluated and found to improve the accuracy of bait distribution. During 1993-1997, when a lower sowing rate of 5 kg/ha was adopted operationally by regional managers, control effectiveness was unchanged but annual savings of around $9 million accrued. Because of the lack of suitable sowing machinery, a bucket was developed to permit faultless distribution of baits at lower rates, demonstrating the possibility of yet further cost-savings.

The possibility of seasonal food availability affecting bait acceptance was investigated in three different forest habitats. Dyed baits were aerially distributed on 100 ha at each site in each season over two years. In each trial, fat-based condition indices of possums were calculated and the abundance of possum-preferred plant foods described. Bait acceptance was consistently high (85-100%) in the 24 trials, and was not influenced by either condition or availability of preferred foods. It seems likely that seasonal variation in operational effectiveness is caused by either the availability of sharply seasonal, scarce foods that possums may feed on intensively for brief periods, or by warmer temperatures that render 1080 less effective.

The influence of 1080 on acceptance of (rhodamine-dyed) baits was investigated in a field trial. Examination of possums for dye-marking showed that 25% of possums refused to eat either a lethal quantity of bait or any bait at all, compared with 98% of possums eating non-toxic bait. This indicated that 1080 is aversive to possums, which is a potential major reason for their surviving control operations. Pen trials were therefore conducted to further examine the problem and to seek solutions. Toxic carrot baits were rejected by 27.5% of possums, equally by smell and taste aversion, whereas toxic cereal pellets were rejected by 34%, mainly by taste aversion. Orange and cinnamon were shown to be among the most preferred of 42 flavours tested and, when applied to toxic baits, 1080 was effectively masked. Bait refusal was reduced to ≤7%, the same as that recorded for possums presented with flavoured non-toxic baits.

For long-term control of possum populations, aerial 1080 baiting can be used sequentially with other poisoning methods. However, the compatibility of these methods is dependent on

the likelihood of possums developing bait shyness if sublethally dosed. Studies were therefore conducted to characterise and compare the four main toxicants used (1080, cyanide, cholecalciferol and brodifacoum) for induction and mitigation of bait shyness. Shyness was induced in approximately 80% of possums sublethally dosed with cyanide, 60% with 1080, 20% with cholecalciferol, and 0% with brodifacoum. Cyanide and 1080 shyness were found to persist in many possums for at least 12 and 24 months, respectively. Use of alternative bait types, and of baits containing an alternative slow-acting toxin (brodifacoum) were shown to be effective ways of overcoming shyness.

This, and other related research, is reviewed to provide operational specifications that maximise the likelihood that *all* targeted possums will (i) encounter bait, (ii) eat it, and (iii) die. The likely future use of aerial 1080 baiting is described and the technological, economic, environmental and social constraints on its sustainability are discussed. Finally, the uptake of the research by possum managers is considered, and areas identified in the thesis where information is incomplete are summarised as prioritised topics for further research.

Keywords: brushtail possum, *Trichosurus vulpecula*, vertebrate pest control, baits, aerial baiting, bait palatability, bait acceptance, bait aversion, bait shyness, sodium monofluoroacetate, 1080, cyanide, cholecalciferol, brodifacoum.

Contents

Tables

Figures

Chapter 1. Historical Context and Structure of the Thesis

1.1 Introduction

The brushtail possum (*Trichosurus vulpecula*) is a nocturnal, tree-dwelling marsupial native to Australia where it occurs over much of the continent including Tasmania. Its introduction to New Zealand has led to damage and threats that currently rank among the most serious pest problems facing any nation in the world. Currently, $89 million is being spent annually controlling possum populations in key areas, and $13 million in conducting related research (NSSC 2002). In addition, continuing annual damage to agriculture (including forestry, horticulture and erosion-control plantation) has been estimated at around $40 million (Bertram 1999). However, even greater concern is placed on the potential annual losses of beef, dairy and venison exports, valued at $9.6 billion for 2001 (Game Industry Board 2002; Meat New Zealand 2002), and the major ecological cost exacted through the possum's impact on native biota. Together, these impacts place the possum among the most important of vertebrate pests affecting any country, rating the possum in New Zealand as significant a pest as the rabbit (*Oryctolagus cunniculus*) is to Australia, and rodents are to many developing nations.

In this chapter, I first provide the background context in which my thesis research has been conducted. I describe the history of the introduction and liberation of the possum into New Zealand, based on the account provided by Pracy (1974). The emergence of the possum as a major vertebrate pest is then traced through the recognition of damage and threats attributed to the animal, particularly during the last 50 years. I then summarise the early development of the aerial control method, the control strategies that were established once it was recognised that a coordinated approach was needed on a national scale, and the changing sociopolitical context that has influenced that national control effort. With this context described, I then outline the structure of the thesis which is summarised by a flowchart (Fig. 1.1). This was developed at the outset of my research to identify and logically arrange the studies needed for optimising aerial control of possums, and it has served as a useful framework over a 25-year period.

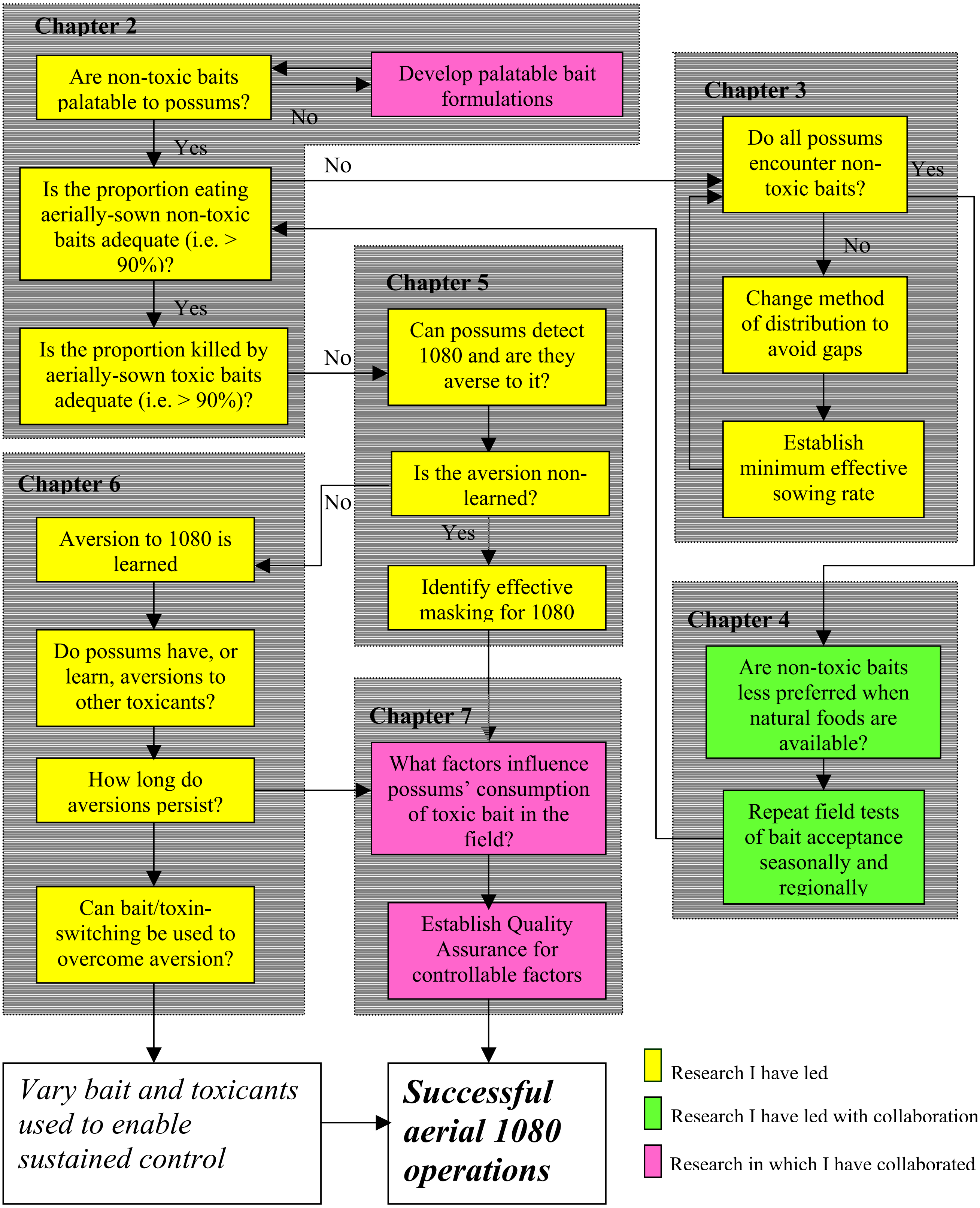


Fig. 1.1 Flowchart showing logical arrangement of technical questions posed and solutions sought in optimising and sustaining aerial 1080 control operations. Shaded boxes indicate the structure of the thesis.

1.2 Historical context of the thesis

1.2.1 Introductions from Australia

Captain J. Howell is credited with making the first introduction of possums (number unknown) in 1837 near Riverton, Southland, but these failed to establish and the first successful introduction was attributed to Mr C. Basstian in 1858, also near Riverton (Pracy 1974). A further 28 groups of possums were introduced to the wild between 1865 and 1911, mainly by acclimatisation societies, with the intention of establishing a fur trade (McDowall 1994). Usually, between one and 12 animals were introduced on each occasion, although a group of 42 possums from mainland Australia was introduced by the Canterbury Acclimatisation Society to Banks Peninsula in 1865. The peak period of introductions was between 1890 and 1898. The records of introductions compiled by Pracy (1974) show that of the 30 known introductions, numbers of possums introduced were recorded for 21, totalling 188 animals. (Nine further possums were introduced in seven groups between 1913 and 1924 as pets, and are presumed not to have been liberated.) As the average number introduced on each occasion was 9.1 (standard deviation 8.5), I estimate that around 280 possums were introduced to New Zealand forming the basal stock from which today's national population has developed. This was estimated at 60-70 million in 1990 (Cowan 1991), but subsequent control efforts have probably reduced this to around 53 million at present (B. Warburton pers. comm.).

Most possums in mainland Australia have mainly grey fur, whereas those from Tasmania typically have a mixture of brown and black fur. The dark-furred Tasmanian possums were preferred during the introductory phase on account of their generally superior fur-quality compared with that of possums from mainland Australia, resulting in 86% of the introduced animals being of the dark type. It is fortunate that the possums introduced to New Zealand were all obtained from eastern parts of Australia (Pracy 1975). This is because possums in western Australia evolved among plants which contain fluoroacetate (see section 1.2.5) resulting in a tolerance to 1080 poison (a synthetic form of fluoroacetate) that is over 100 times greater than in possums from eastern Australia where fluoroacetate-containing plants are absent (Oliver *et al.* 1977). If western Australian possums had been introduced, 1080 poison would later have been unsuitable for possum control in New Zealand.

1.2.2 Liberation and spread within New Zealand

Descendants of the introduced possums are known to have been liberated at 464 locations, mainly by private individuals during 1837-1861, acclimatisation societies during 1870-1930, and hunters who continued to liberate them illegally. The resultant distribution of possums up to the late 1940s was mapped by Pracy (1974) and updated based on four national surveys (Pracy 1981) from which Batcheler & Cowan (1988) calculated that 54% of New Zealand was occupied by possums in 1948-50, 84% by 1961-63, and 91% by 1980. In 1994, it was estimated that possums were present in more than 91% of the country (Parliamentary Commissioner for the Environment 1994), with only the highest mountains, a few remote South Island valleys, and heavily urbanised areas remaining free of possums.

While expansion was rapid during the 1950s, populations had started to decline in many areas by the early 1960s. It has been estimated that population 'establishment' typically takes around 30 years following introduction (Pekelharing 1979). The population initially increases slowly then rapidly, eventually being checked by over-population, resulting in the population commencing a decline towards an ‘equilibrium’ in its, by now, depleted environment. Of 390 populations surveyed (Pracy 1981) only 6 were in decline in 1948-50, but by 1961-63, 111 were in decline, 190 were declining by 1974, and 390 by 1980. It has been estimated that about two-thirds of the national possum population was present in the North Island, and one-third in the South Island (Batcheler & Cowan 1988). This is probably due to the North Island’s warmer climate, relatively low altitude, and more diverse forests (hence providing a greater food resource).

1.2.3 Damage and threats to native ecosytems

Awareness of the potential for ecological damage by introduction of alien species appears to have been lacking in New Zealand during the latter part of the 19th century, despite the following caution being expressed in the British journal *Nature* in 1872 (as noted in Pracy 1974). This referred to “the silly mania for acclimatisation” which it said was at that time being: “so warmly fostered by many well-meaning though ill-advised persons, and nowhere more so than New Zealand. In a reckless way, animals of extremely doubtful advantage have been transported to the Antipodes and, unaccompanied by any of those checks which keep natural fauna balanced, the importations will inevitably become the greatest of nuisances”.

Eminent botanists of the early part of this century such as Kirk (1920), Perham (1924), and Cockayne (1928) supported the introduction of possums believing that they would not have a deleterious effect on New Zealand flora. Local concerns soon developed, however, with the Forest and Bird Protection Society in the 1920s commencing a campaign opposing acclimatisation of the species, and the Forest Service in the late 1930s recognising damage to exotic trees planted for timber production. By the late 1940s, damage was becoming conspicuous throughout large tracts of indigenous forest, and dietary studies were undertaken confirming possum browse as the cause of the emerging widespread damage (Pracy & Kean 1949). Damage was particularly noticeable in the rata/kamahi forests of Westland (e.g. Holloway 1959) and the central North Island (e.g. Elder 1965). A radical change in official policy occurred in response to this emerging scientific evidence, as described by Clout & Eriksen (2000). The government introduced possum control in 1947 when the use of poisons for possum control was first legalised, all restrictions on the taking of possums were cancelled, and penalties were introduced for the keeping or liberation of possums. In 1951 the government introduced a bounty system to encourage possum control but this failed to control both possum numbers and the spread of the animal. Conversely, the scheme is believed to have encouraged some possum trappers to deliberately spread possums into new areas to provide a source of income. The possum was declared a noxious pest in 1956 when control of all Noxious Animals was transferred from the Department of Internal Affairs to the NZ Forest Service (NZFS), initially under the Noxious Animals Act 1956 and later under the Wild Animal Control Act 1977. Since 1987, the Department of Conservation, as successor to the NZFS, has continued possum control for the conservation of native biodiversity. In seeking to better understand both the impacts and control of introduced mammals, the NZFS established the 'Protection Forestry Division' in the early 1960s as part of its research department, the Forest Research Institute (Kininmonth 1997). Based at Rangiora, this Division initiated considerable research in the 1970s investigating the role that possums were playing in the erosion of steep lands, their impact on forest composition and dynamics, and their competitive effect on populations of native birds. This research, which has continued to the present, provides much of the justification for possum control in native forests.

The present concerns over possums' impacts on native biota in relation to plants are summarised by Payton (2000). While certain plant species (e.g. rata, kamahi, pohutakawa, totara, kohekohe, five-finger, and fuchsia) are commonly extensively damaged, the susceptibility of individual plant species and communities appears to be strongly influenced by the stability of the landscape. In landscapes that are frequently disturbed by natural events, such as earth movements, destructive weather, or insect attack, seral (i.e. fast-colonising and quick-growing) plant species become abundant. Many of these species are highly palatable to possums, possibly due to their rapid uptake of nutrients from the disturbed site. Thus in unstable landforms, such as the 'schist' belt underlying much of the rata-kamahi forest of Westland, an abundance of seral species leads to an abundance of possums that results in damage also to the dominant forest tree species. As the landform matures, the frequency of disturbed sites and seral vegetation declines. Seral species are then replaced by species characteristic of low-fertility sites, which are little browsed by possums.

Since an estimated 20% of New Zealand's flowering plants are as yet unnamed, and new species are still being discovered (including the recently-discovered *Akama nubicola* which is highly vulnerable to possum browsing (Samson & Green 2003)), significant browsing impacts on native flora may be occuring of which we are, as yet, unaware.

The main impact of possums on native animals is predation, rather than competition for food, as summarised in Sadleir (2000). Stomach and faecal analyses have shown that possums eat birds and many species of insects. Direct observation has also confirmed that the possum predates birds. My own observations of the predation by captive possums of a sparrow (Morgan 1981) renewed interest in the possibility that, while mainly herbivorous, the possum may at least be an opportunist predator. Subsequent video observation has confirmed that possums eat adult birds, their chicks, and eggs. It is now thought that the possums' role in the decline of species such as kokako is due more to such predation rather than competition for the foods, despite evidence of dietary overlap (Fitzgerald 1984; Cowan & Waddington 1990).

1.2.4 Damage and threats to agriculture

The possum's status as an agricultural pest is primarily due to its role as a reservoir of bovine tuberculosis (Coleman & Caley 2000). Since bovine Tb was identified in possums in Westland in 1967, the disease has spread in both possum populations and adjacent cattle herds such that infected possum populations now occupy about 25% of the country. It is estimated that there is a 20% chance (over the period 2001-2013) that key markets for agricultural produce will be lost if New Zealand authorities are unable to demonstrate that infected herds do not exceed 0.2% of the total of the nation's cattle and deer herds (Animal Health Board 2001), a threshold below which is accepted internationally as being 'Tb-free'. While recent Animal Health Board data indicate a 60% reduction in the number of infected herds between 1995 and 2000, the disease continues to spread into new populations of possums. Mere continuation of the present control effort is predicted to be incapable of reversing this trend as previously uninfected herds will continue to come into contact with infected possums and other vectors (Animal Health Board 2000). Consequently, a new National Tb Pest Management Strategy is designed to approximately double control expenditure (and, hence, land area under control) during the next 10 years (Animal Health Board 2001). It is expected that much of this increase will be achieved by aerial application of 1080 baits for possum control.

The impact of possums on agricultural crops is reviewed by Butcher (2000) who concluded that it remains largely anecdotal and unquantified. Competition between stock and possums is only likely to be significant when grass is in short supply. While damage to horticulture is widespread, with reports of damage to at least 46 varieties of fruit and vegetable crop, it is seasonal, patchy, and only prevalent in areas close to preferred possum habitat. Damage to forestry is estimated to vary between $282 and $840 per hectare, assuming a 5% loss at planting, and most forestry companies control possums (and other browsing pests) to avoid such losses. Other types of impact, which can be very significant to individual farmers, include damage to willows and poplars planted for land stabilisation, and depression of the honey harvest as a result of possums competing with honeybees for nectar-rich foods. Possums also carry a range of diseases and parasites that can infect domestic stock and humans (Cowan *et al*. 2000).

1.2.5 Development of aerial 1080 control

With the recognition of the threats posed by possums in the early 1950s, the N Z Forest Service initiated the development of an aerial control method capable of rapidly treating large areas of vulnerable or damaged forest. The early development of aerial control of possums is documented mainly by four unpublished reports: Batcheler (1958 and 1978), Pracy (1961) and Martin (1973). Other details have been sourced from a published history of forestry research (Kininmonth 1997). The method that was developed combined overseas experience in the use of 1080 (sodium monofluoroacetate) as a poison for controlling rabbits and rodents with local expertise in the development and use of aerial topdressing technology.

Fluoroacetate, the toxic component of 1080, occurs naturally in some plant genera in South Africa (*Dichapetalum*), South America (*Palicourea*), and Australia (*Gastrolobium, Acacia, and Oxylobium*). Many mammalian species that evolved within the range of these plants have adapted to browsing them by developing an unusually high capacity to detoxify fluoroacetate (Oliver *et al*. 1977). The tolerance of possums to 1080 in Western Australia is over 100 times greater than possums from Eastern Australia (Oliver *et al.* 1977).

Sodium monofluoroacetate was first produced synthetically in Belgium in 1896, but it was not until 1944 that it was first used experimentally as a rat poison (under the code name 'Compound 1080') at the Patuxent Wildlife Research Center in the United States and in the late 1940's as an coyote poison under the code name 'Compound 1080' at the Denver Wildlife Research Centre, also in the United States (Rammell & Fleming 1978). Traditionally, it has been described as an odourless, non-volatile and virtually tasteless fine white powder, although as my research later showed, it is clearly perceptible to many possums (see Chapter 5). Fluoroacetate is metabolised to fluorocitrate which inhibits the tricarboxylic acid cycle by combining with the enzyme aconitase, which is required for the conversion of citrate to isocitrate. This slows down the release of hydrogen atoms to the electron transport chain and the production of ATP (adenosine triphosphate) resulting in a slowing down of available energy, and possums die from cardiac failure generally in 6-18 hours (Hayes & Lawes 1991).

An inspection visit was made in 1954 by two staff of the NZ Department of Agriculture to view the use of 1080 carrot baits for controlling rabbits in Tasmania (Cairney & Forrester 1954, cited in Batcheler 1958). The technique was also proving effective in Victoria (Douglas 1959), and as a result, aerial 1080 baiting largely replaced the earlier use of ground-laid arsenic baits in rabbit control in New Zealand from 1956 on. In that same year, possums were declared a noxious pest and their control formally became the responsibility of the NZ Forest Service. Given the success of aerial 1080 baiting against rabbits, an intensive period of method development followed to adapt the technique for controlling possums.

The first studies on the susceptibility of the possum to 1080 were conducted in October 1956 by Dr R.I. Kean (of the Animal Ecology Division, DSIR) who concluded that a dose of 2-3 mg/kg was needed to ensure death of most possums. Trials were also initiated in 1956 by L.T. Pracy (of the NZ Forest Service) to develop suitable formulations of bait. Carrot had been used effectively as a bait for rabbit control for many years, and was known to be highly palatable to possums. Carrot baits were impregnated with 1080 using a specially constructed 'Gibson' dicing machine. A green dye was also incorporated based on trials that established green dye as an effective bird-deterrent bait additive (reported in Batcheler (1958), and later published by Caithness & Williams (1971)).

Interest soon arose in the development of alternative baits. This was because carrots were usually unavailable in large quantities during the winter months, when it was assumed that control would be most effective against possums due to their poorer body condition at that time of the year. Furthermore, the rapid degradation of carrots was considered an important disadvantage when it was envisaged that large operations might be conducted over prolonged periods if interrupted by bad weather. Pracy (1961) identified the key specifications for development of a successful bait in the early development of the aerial control method. These were:

- high palatability to possums
- standard-sized baits each carrying a lethal dose of 1080
- unattractiveness to birds
- stability in storage, transit, and aerial application
- durability in the field
- size suited to highest acceptance by possums
- ease of flow from an aircraft hopper

These specifications are still regarded as the most important parameters in the achievement of effective aerial 1080 control operations, as detailed in Chapter 7.

Pracy began field trials of pellet baits made from 'pollard' (i.e. the husks and chaff left after wheat has been milled), molasses and glucose at Rabbit Board Supply Factories at Wanganui and Waimate. The 1080 poison was incorporated as a bait ingredient during manufacture rather than sprayed on to the bait surface at the operational site, as was the case with carrot bait. Surface application was considered likely to soften baits causing breakage and difficulty in aerial distribution, and a higher rate of loss of the toxin under rainfall. Between 1956 and 1960, six trials were conducted (the first being in Mount Bruce State Forest, 3-14 December 1956) in which 1080-treated pollard baits were distributed from topdressing aircraft at estimated application rates between 2 and 7 kg/ha and population density reductions were assessed by changes in the frequency of capture of possums caught in leg-hold traps (Batcheler *et al.* 1967). Kills varied between 50 and 98% (Batcheler 1978) and it was concluded that varying concentrations of 1080 and bait size were two factors that markedly influenced results. These initial trials were sufficiently encouraging to establish aerial poisoning as the major possum control method used thereafter by the NZ Forest Service. However, results continued to be variable and unpredictable. Of 18 operations and 15 trials in the 1960s and 1970s, the mean kill was 69% (Batcheler 1978). This would be regarded as 'failure' today. Kills of 85% or more, which would today be considered as effective operations, were achieved in only 12 (36%) of the operations and trials. Consequently, the NZ Forest Service initiated new research at its Rangiora-based Forest and Range Experimental Station, aimed in part to determine the causes of such failures.

Field studies in Westland conducted by the new research group showed that variation in body condition of possums (using techniques developed by Bamford 1970) was correlated with poisoning success (Bamford & Martin 1971), and this led to the view that seasonal and regional availability of natural foods may be an important determinant of operational effectiveness. A major factor contributing towards poor success of some operations during the first 10 years was considered by Martin (1973) to have been the poor durability and handling qualities of baits. Furthermore the pellet formulation used was expensive, resulting in the more extensive use of carrots which were now being grown under contract for control operations, making them available at most times of the year. To address these problems, Martin experimented with a wide range of formulations with the aim of developing pellet baits that were capable of being stored for prolonged periods without deterioration (Martin 1973). Martin noted that progress was being impeded by limited funding, and commented that since the possum "is now believed to act as a reservoir of tuberculosis …it is difficult to understand why research into methods of controlling this animal is being so poorly supported. The longer the problems of assessment, prediction, bait development and behaviour are left unsolved, the greater will be the economic loss, due to what in effect are often 'hit' or 'miss' operations."

In 1975, the Rangiora research station became part of the Forest Research Institute. As the major organisation undertaking research on introduced mammals (summarised in Orwin (1973)), its main focus changed in the mid-1970s from deer to possums, which were coming to be regarded as New Zealand's foremost vertebrate pest. It was during this period that I started my own research (in January 1975) on the improvement of aerial control of possums, initially continuing Martin's programme of bait development.

1.2.6 Development of bait manufacturing and machinery for aerial delivery of baits

Bait production. Pracy's early trials led to carrot and manufactured cereal-based pellets being regarded as alternative options for aerial baiting of possum populations. Machinery had already been developed for converting carrots into 1080-treated baits for rabbit control. These early machines (Urquhart, Bentley, and Gibson) all tended to produce baits of very variable size, irregular shape, and with a large component of chaff (a particular hazard to birds). A significant improvement in the use of carrot as a bait was made during 1972-73 when the Reliance Engineering Company (Nelson) developed a new type of carrot cutter. Unlike the earlier cutters, the Reliance cutter produced a more regular-sized, predominantly cube-shaped bait with less chaff (Batcheler 1982). Used in conjunction with sieving screens that were developed in the late 1970s in response to continuing reports of bird deaths (e.g. Harrison 1978), the Reliance cutter became accepted as the best available machine for preparation of carrot bait. Ultimately, it was developed into an 'all-in-one' machine that could cut and screen carrot, and treat pellet baits with 1080 solutions (Batcheler 1982). Plant for manufacturing cereal pellet baits was installed at government-owned factories at Wanganui and Waimate, and during the 1990s the enterprise was privatised and extensively upgraded to meet the demand for greater output and higher quality of its products.

Aerial delivery machinery. In trials conducted by Pracy between 1956 and 1960, much was learned about the use of agricultural topdressing aircraft for rapidly distributing possum baits over large tracts of forested country. During the early 1970s, aerial topdressing companies began to develop machinery specifically designed for distributing possum baits. Both fixed-wing aircraft and helicopters have been used since this time, and a number of adaptations were made to the sowing machinery (Spurr 2002), largely in response to the differing nature and application rates of baits compared with fertiliser.

Increasing swath-width. The efficiency of aerial distribution of particulate materials is partly influenced by the width of swath achieved. Possum baits, being of a greater particle size (2-12 g) than fertiliser (0.2-1g), fall in a steeper trajectory leading to small swaths of approximately 10-m width, whereas fertiliser spreads further giving a typical swath width of around 100 m. Fixed-wing aircraft were fitted with a range of devices beneath the hopper outlet to direct airflow and baits rearward and outward in swaths of up to 80 m. Helicopter fertiliser buckets were modified by the use of higher-powered motors or by coupling to the helicopter's hydraulic system to provide the outlet 'spinner' (i.e. a rotating delivery plate or series of radiating tubes) with greater centrifugal force, leading to swaths of up to 100 m.

Decreasing bait-breakage. The softer texture of possum baits, particularly cereal pellets, compared with fertiliser granules resulted in baits being damaged during transit through sowing machinery. Such small pieces of bait were sublethal to possums, hazardous to birds and wasteful (Morgan 1994a). The problem was particularly common in helicopter sowing buckets. While delivery by fixed-wing aircraft depends on a passive flow of baits by gravitational force, helicopter-delivery utilises considerably greater force to rotate the spinner plate. Baits frequently became damaged on encountering this plate, and thereafter, on impact with the legs and other parts of the sowing bucket after leaving the spinner plate. Consequently, aerial operators experimented with various designs to reduce impact with the spinner plate, and developed cushioned or retractable legs to reduce bait breakage.

Consistency of flow. Blockages in the output stage of sowing machinery was a common problem when using either carrot baits (which tended to stick together due to the surface coating of 1080 and dye applied) or cereal pellet baits (which were softer and tended to form clumps). To maintain an even flow of baits during distribution, agitators were designed that maintained slow movement in the baits approaching the output stage of aircraft hoppers and sowing buckets. Another common cause of interrupted bait flow was the build-up of pellet fragments underneath the drive-belt for the spinner plate resulting eventually in the belt being dislodged from the pulley. Bait flow was stopped and hold-ups occurred while repairs were undertaken. While some success was achieved in using guards to overcome this problem, most operators eventually adopted the use of hydraulically powered buckets that dispensed with the need for belt-driven spinners.

Achieving lower rates. While fertiliser delivery machinery had been developed to achieve application rates of 100 kg/ha or greater, typically possum baits were distributed, initially, at much lower rates of 10-30 kg/ha. Eventually, my research indicated that even these application rates were unnecessarily high and could be reduced tenfold (Chapter 3). This was generally achieved by reducing the size of the output aperture in the aircraft hopper or sowing bucket. However, this tended to exacerbate the problem of clumped baits preventing flow. In response to this problem, newly designed buckets appeared during the late 1990s including one that I co-developed and patented, the 'SowLow' bucket (Chapter 6). This bucket utilises a separate variable-speed motor to control the speed of a bait 'metering' device before bait is delivered through a continually wide-open output aperture to the conventional spinner plate. Hence the application rate of bait is controlled by the rate at which bait is metered out of the bucket.

1.3 National strategies for possum control

The need for possum control originated from the realisation and eventual wide acceptance that possums were causing significant damage to both native and exotic forests, and to this end the Environmental Forestry Division of the NZ Forest Service developed a strong capability in the early 1970s to conduct possum control programmes in critical habitats. Initially these were in Westland, the Ruahine Range, the Wairarapa, and Kaingaroa Forest, but later (under the Department of Conservation) possum control was implemented to protect an increasing number of conservation values in forested regions throughout New Zealand.

Perhaps the most significant factor influencing strategy for controlling possums was the identification in the late 1960s of their role as a reservoir of bovine Tb (Ekdahl *et al.* 1970), leading to major concern over the loss of beef, dairy and venison exports. The Agricultural Pests Destruction Council (which coordinated regional pest boards) expanded its capability to undertake possum control as well as continuing to control rabbits. Possum control programmes involving both aerial and 'ground' control methods were initiated with the aim of reducing the likelihood of cattle becoming infected with Tb carried by possums. During the late 1970s and throughout the 1980s, the majority of possum control was carried out towards this end. The consequence of this shift in focus was that gains made in conservation-oriented aerial control programmes were lost as follow-up control was neglected. Limited control funds were instead increasingly aimed at controlling the spread of Tb. By the end of the 1980s it was evident that the piecemeal approach to possum control was inefficient. Coordinated strategies at the national level to meet the dual aims of conservation and agricultural protection were needed. In 1993 two such strategies were introduced. The Animal Health Board launched a 5-year plan (Animal Health Board 1993) in which control priorities were established for protection of cattle from Tb. By 1995 this plan had succeeded in reversing the upward trend in Tb-infected herds that had been evident since 1980 (Animal Health Board 1999). Nevertheless, the Board's next strategic plan, introduced in 2001(Animal Health Board 2001), argued that possum control effort must be more than doubled to reduce infected herds to less than 0.2% of the national total. Failure to achieve this would result in a 20% chance of losing $1.3 billion worth of exported produce to US and European markets within 10 years (Animal Health Board 2001). Similarly, the Department of Conservation introduced a 10-year plan (Department of Conservation 1994) for sustained protection of the most valuable parts of the national conservation estate.

Central to both of these strategies was the principle that control must be both economically and technically sustainable. This necessitated the prioritisation of areas for control. 'Endemic' areas were targeted as the highest priority for possum control in mitigating the spread and effects of bovine Tb. Conservation habitats were ranked for priority on the basis of the most relevant parameters such as biodiversity, presence of endangered species, vulnerability, etc., using procedures previously developed to define priority areas for goat control on conservation land (Parkes 1990). Long-term funding was then committed under the two strategies to ensure that control would be sustained in the areas of highest priority. Advances in the technical feasibility of control have created gains in efficiency that are expected to improve the chances of success of these strategies and, furthermore, to increase the extent of control that can be undertaken. Thus areas originally of lower priority may become targeted for sustained control.

1.4 Changing sociopolitical context of possum control

The wide geographical scale of possum impacts, and the progressive increase in effort made to control the most critical populations over the last 45 years, have resulted in a wide range of people and organisations taking an interest in both the nature of the problems and the way in which possum control is undertaken to deal with them. Scientists became aware of the need for a stronger technical basis to underpin effective control (e.g. Martin 1973), and the national research effort now directed towards possum control is in the order of 100 staff having a major focus on possum research (D. Wright, pers. comm.). Farmers, politicians, and the Animal Health Board sought greater efficiency to facilitate a sustainable national Tb control programme that would insure against trade damage (e.g. Livingstone 1993). More than 70% of a cross-section of the general public wish to see possums exterminated, with 52% favouring poisoning as the most acceptable method (compared with 10% favouring biocontrol) (Fraser 2000). Nevertheless, aerial 1080 poisoning has met with particular criticism for its perceived indiscriminate effect on ecosytems (e.g. Watts 1994). Planners in the 1990s, under the guidance of the Resource Management Act and the Biosecurity Act, have focussed on the need for control to be sustainable, both economically and technically. Worldwide, consumers have become increasingly concerned about toxic residues in food and the humaneness of farming systems, and perceptions are formed that influence purchasing behaviour (Williams 1994). To avoid market resistance to New Zealand beef and dairy exports, Livingstone (1993) suggested that international consumer opinion should be monitored as a basis for formulating acceptable pest control strategies.

The resulting mixture of opinions, experience, and visions has provided a dynamic context within which both possum researchers and managers have had to attempt to find and implement broadly acceptable ways of controlling possums. The development and use of aerial 1080 control has undoubtedly attracted more interest than any other vertebrate pest control method used in New Zealand. This thesis describes much of the research undertaken, by myself and others, to refine the technique.

1.5 The international scientific context of possum control research

Much of the international research literature on vertebrate pest control is represented in 'proceedings' of a number of conferences held periodically. The California-based Vertebrate Pest Conference (biennial since 1960), the Australasian Vertebrate Pest Conference (irregularly since 1961), the European Vertebrate Pest Conference (biennial since 1999) and the Australasian Wildlife Management Conference (annual since 1987) are the major fora at which international vertebrate pest issues are presented, and these are supplemented by other, more broadly focussed fora such as the International Wildlife Management Congress (irregularly since 1993). From participating in many such gatherings and using their various 'proceedings', I perceive some key differences that distinguish the position of New Zealand and Australia from other developed countries with respect to pest problems and approaches to solving them.

Vertebrate pest issues in the United States and Europe (the sources of a substantial proportion of the international literature) are typified by pests and their impacts being more localised and largely due to avian species. Packham & Connolly (1992) surveyed vertebrate pests and their damage in the United States and found the highest priority vertebrate pest problems, catagorised by resources that were damaged, were, in order: grain, domestic nuisance, livestock, structures, aircraft, and fish. Seven of the the top ten ranked vertebrate species were avian. Their data indicate an array of largely commensal impacts that are geographically highly fragmented. Larger-scale problems more typical of the major concerns in Australasia (caused by mammalian pests such as possums, ungulates, canids, mustelids, and rodents) were prioritised lower as follows: disease (12), pasture-range (14), and wildlife (17). This difference probably arises from the fact that most Australasian vertebrate pests were introduced and are less constrained by the population regulating mechanisms that operate in their country of origin (e.g. predation, plant defenses, and greater competition for resources). In addition to their greater scale, such pest problems in Australasia are usually more physically separated fron human populations than in the United States and Europe, where higher human population densities have brought communities and pests closer together. Furthermore, the more strongly agriculturally-based economies of New Zealand and Australia may contribute towards greater public ownership of agricultural pest problems and their solution. By contrast, the predominantly urban cultures of the United States and Europe may predispose human populations to a poorer understanding of pest issues (unless people are directly affected by a pest) (Acord 1992), and a greater reluctance to support control of populations of animals that are native rather than introduced. Thus, the differing geographical and cultural contexts of vertebrate pest problems have, I believe, contributed to the development of differing pest management policies and practices. As a consequence, much of the most relevant literature in my research has originated in Australasia. One area in which a body of international literature provided a useful theoretical foundation for my research is the topic of learned aversions which forms the focus of Chapter 6.

The relevance of my research to other countries may therefore be limited due to these differences. However, the approach I have followed may be of value. The ordering of key questions for investigation in a logical and efficient manner (as will be described in the following section) is an approach that does not seem to have been adopted with regard to other major vertebrate pests. Most ‘conventional’ control technology (i.e. not biological control) appears to have been developed in a somewhat piecemeal manner as particular problems have arisen (although the present development of biocontrol methods for vertebrate pest control in Australasia is following a long-term strategy under the guidance of the bi-national Marsupial Cooperative Research Centre based at Macquarie University, Sydney). Apart from helping achieve greater efficiency, such an approach may improve the focussing of effort and uptake of findings in the development of technology for controlling vertebrate pests such as foxes, feral pigs and cats in Australia, ground squirrels in the United States, and grey squirrels in Europe.

1.6 Overview of the thesis

Most of my past research, carried out during 1975 to the present, on maximising the effectiveness of aerial 1080 control of possums has been published in peer-reviewed papers. However, the work has not been synthesised in a manner that brings together the various components in the logical manner in which they were planned. The thesis aims to achieve this synthesis by integrating past research that I completed during 1975-97 with new research carried out during 1998-2002 (i.e. the term of this Ph.D. study). In this thesis, I distinguish these two phases as being 'past' and 'new' research, respectively.

1.6.1 General aims of the research

Past research. My past research was initiated as a result of the growing recognition of the possum's importance as a pest during the 1970s. Possum managers needed to improve the effectiveness of aerial control since operations were not consistently effective (Batcheler 1978; Spurr 1993). Modelling showed that if average kills of around 70%, that were typical of the period, could be increased to 90%, the period for the population to recover to 95% of the initial density would be increased from 9 years to 14.5 years (Spurr 1981). This has been confirmed recently by Veltman & Pinder (2001) and, furthermore, the authors predict that possum populations could be eliminated in 30 years with aerial 1080-operations repeated at 6-year intervals .

Therefore, as a starting point for my research, I posed the question: Why do possums survive aerial 1080 control operations?. Research was conducted to identify the factors contributing to survival, and most importantly, to find appropriate ways of reducing survival. This main question provoked the formulation of a number of more specific questions that were structured in the form of a flow chart (developed in the late 1970s and first published in Morgan 1982) which formed a logical sequence of experimental hypotheses for my research investigations (Fig 1.1). The flowchart illustrates the basic structure of this thesis. My past studies on effectiveness encompassed: the palatability of baits and acceptance of baits by possums (Chapter 2), improving the aerial distribution of baits and reducing bait application rates (Chapter 3), and identifying and overcoming possums' innate aversion to 1080 (Chapter 5).

New research. Occasionally, contemporary aerial 1080 operations fail unexpectedly, despite high standards of operational management. It has long been suspected that possums' acceptance of bait may be poorer during times of abundance of naturally occurring, favoured foods (e.g. Batcheler *et al.* 1967). A new 3-year study was therefore conducted, as part of my thesis work, to investigate the relationship between availability of such foods and operational effectiveness (Chapter 4). By the early 1990s most of the key factors determining the likely effectiveness and efficiency of aerial control operations had been examined and operational procedures consequently improved. To ensure that prevention of possum damage and disease transmission is sustained, agencies have in recent years begun to follow 'initial' control operations with ongoing 'maintenance' control operations. While initial operations often involve aerial 1080 baiting, maintenance operations commonly involve ground-based application of poison baits and this is generally conducted annually, or more frequently, in many locations. This repeated application of poison baits has led to the emergence of 'bait shyness' as a threat to the sustainability of possum control. Consequently, I initiated a series of experiments (mainly conducted during my thesis term) to assess the likelihood of bait shyness developing towards, not only 1080 baits, but also baits containing other commonly used toxicants. The aim of this new research (Chapter 6) was to provide a basis for establishing sustainable control strategies to follow initial reductions achieved by aerial 1080 operations. The importance of quality standards in the conduct of aerial 1080 operations is reviewed (Chapter 7) based on new research in which I participated. Finally, the overall sustainability of aerial 1080 control is discussed (Chapter 8) in the broader context of not only technological factors, but also environmental sustainability, costs and benefits, and community views.

1.6.2 Specific objectives

In the planning of this thesis, the objectives were therefore:

1. To summarise and integrate my **past research** to improve the effectiveness and efficiency of aerial 1080 control of possums (Chapters 2, 3, and 5).
2. To determine if the effectiveness of aerial 1080 control operations is affected by the availability to possums of naturally occurring foods in different seasons and habitats (**new research**, Chapter 4).
3. To determine if bait-shyness is induced by sublethal doses of 1080, cholecalciferol, cyanide, and brodifacoum, to determine the persistence of bait shyness, and to test use of alternative baits (i.e. bait-switching) as a means of sustaining control (**new research**, Chapter 6).
4. To describe **new research** (in which I collaborated) to establish quality-standards for preparation of 1080 baits (Chapter 7).
5. To discuss the technological, ecological, economic, and sociopolitical sustainability of aerial 1080 control (Chapter 8).

Chapter 2. Bait Palatability and Acceptance

2.1 Introduction

This chapter summarises and reviews work I completed during the 1970s on bait palatability and acceptance. A key assumption made by researchers and possum managers in the early 1970s was that the type of bait presented to any particular possum population was one of the most important factors influencing the effectiveness of an aerial control operation. This resulted in a programme of bait development, initiated by J.T. Martin in 1971, from which it was envisaged that a selection of bait types would be produced that would maximise the chances of operational success. An essential prerequisite of such an approach was the availability of reliable methods for predicting the likely effectiveness of baits used operationally. Consequently, on joining the staff of the Protection Forestry Division in January 1975, my first task was to develop such methods.

At the outset I drew a clear distinction between the palatability of bait and possums' acceptance of bait, parameters that had been used somewhat loosely in pest management literature, leading to confusion. Palatability was defined as 'a relative measure of preference by an unknown proportion of the possum population', while acceptance was defined as 'the proportion of a population that eats the bait offered' (Morgan 1982). If both parameters were measured among the same population of possums, I assumed that palatability would indicate likely acceptance of baits under operational conditions. While assessment of acceptance would necessitate distribution of baits on a broad scale (to reduce edge effects and ensure representativeness) and subsequent live-capture of possums to determine proportions eating it, palatability assessment appeared far simpler, requiring far less field effort in assessing the uptake of baits from a series of sample plots. My research into improving the effectiveness of aerial 1080 control of possums therefore started with the development and use of a method to rapidly assess bait palatability in the field.

2.2 Development of a method for assessing palatability of baits to possums in the field

Prior to my research, bait palatability trials, whether for rabbit control (e.g. Rowley 1963; Corr 1971), rat control (e.g. Crabb & Emik 1946; Miller 1974), or possum control

(Pekelharing 1974 unpublished; Jane 1975 unpublished) involved offering a choice of at least two materials simultaneously to the test animal (i.e. 'preference' testing). Preference tests are more sensitive to differences in animal responses than tests that present materials individually (Grote & Brown 1971; Johnston 1981). However, I believed such an approach was unlikely to accurately reflect likely bait acceptance as pest control operations (including possums) usually involved presentation of only one bait type. Accordingly, it was necessary to design a method whereby bait types were offered independently of each other at a series of plots so that a measure of their palatability relative to only the possums' normal food could be gained. Over a period of 18 months a method was developed and used extensively to examine seasonal and regional variation in bait palatability (Morgan 1977 unpublished). Because this work has not been formally published, it is presented here in some detail.

2.2.1 Number of bait plots

A sampling format was chosen to cover an area large enough to be representative of surrounding habitat, and yet be practicably manageable on a daily basis. Initially, 30 plots per bait type per day were used, but later data analysis showed that this could be reduced to 15 plots without appreciable loss of statistical precision. Only in areas of very low population density might this sample size prove inadequate.

2.2.2 Plot spacing

Bamford (1970), using non-toxic bait interference as an index of possum density, showed that possums may, after an initial encounter with bait, look for more. If possums then discover and take more bait, plots are not independent and sampling of possums' responses to bait is not random. Experimenting with various spacings Bamford found that to avoid this 'contagious' effect, in dissected, forested hill country, stations needed to be separated by 40 yards [sic] along lines running up or down hill 200 yards apart. I used these spacings between bait plots to ensure that bait types were presented independently of each other.

2.2.3 Quantity of bait presented at each plot

A second contagion effect investigated by Bamford (1970) was the effect of possums remembering the location of bait stations and returning to them on successive nights. As the palatability of baits was to be assessed in terms of the weights of baits consumed, it was necessary to ensure that sufficient bait was presented at plots so that some bait would remain for unbiased assessment of consumption. Based on preliminary data, Table 2.1 shows the quantities of bait per plot I used in areas of low, medium, and high population density (where density was subjectively assessed on the basis of possum 'sign').

Table 2.1 Quantities (g) of bait laid per plot on successive nights to avoid complete removal in areas where possum populations were subjectively assessed as being of low, medium, or high density.

Population density	Night				
	1	2	3	4	5
Low	150	200	300	300	300
Medium	250	400	600	750	1000
High	650	850	1500	2000	2500

2.2.4 Equal exposure of bait types

Different bait types were laid in a systematic sequence at each successive plot along a line (i.e. A, B, C, D, A, B, C, etc.). The sequence was changed nightly so that, during a trial, each plot was supplied at some time with each bait type. Thus a trial testing four bait types was conducted over 4 nights. To avoid errors in allocating bait types to plots, the systematic procedure was also followed over successive nights. To test whether bait types were exposed equally by this procedure, a trial was conducted using only one bait type for 3 nights. Data were then organised into three groups corresponding to how data would have been analysed in a trial testing three bait types. Equal mean quantities of the three types of bait were eaten ($F_{2,132} = 0.44$, $P = 0.64$) establishing that the design provided for equal exposure of bait types.

2.2.5 Correction of data for climatic effects

To correct for climatic effects causing either weight gain or weight loss, reference samples of baits were placed under wire cages (to prevent interference by possums) in conditions representative of the trial area. An assumption was made that, if baits fluctuated in weight over the night-time feeding period, the average weight of available bait (i.e. recognising that much of the bait would be consumed in the early part of the night) occurred at 2 h after dusk. Reference baits were therefore weighed (to the nearest gram) at this time so that the actual weight of bait eaten at plots could be calculated by proportion. Since:

$R_e/R_m = W_e/W_m$ where, R_e = Wt of reference bait at 2 h after dusk
R_m = Wt of reference bait at dawn

W_e = Wt of bait at trial plots at 2 h after dusk
W_m = Wt of bait at trial plots at dawn

then, $W_e = R_e \times W_m/R_m$.

Since:

$W = R_e - W_e$ where, W = Actual wt of bait consumed at trial plots

then by substitution,

$W = R_e - (R_e \times W_m/R_m)$.

Weights eaten were converted to a percentage of the amounts available:

$W\% = (W/R_e) \times 100$ where $W\%$ = the percentage of available bait eaten.

For analysis, W% was arcsin transformed to normalise the distribution of the data.

2.3 Regional and seasonal variation in palatability of baits to possums

The supposition by possum managers and researchers in the 1970s that possums' responses to baits varied was consistent with studies on the natural diet of possums, which was shown to vary both regionally (Mason 1958; Gilmore 1965; Dunnet *et al.* 1973) and seasonally (Gilmore 1967; Jolly 1976). Moreover, studies on the influence of body condition on operational success confirmed the influence of available food resources (expressed through the develoment of body fat) on possums' consumption of 1080 baits (Bamford 1970; Bamford & Martin 1971). I therefore established a series of field trials in 1976 to determine if bait palatability was influenced regionally and seasonally.

2.3.1 Location and timing of trials

Trials were conducted in areas representative of the range of conditions in which possum control is often warranted (Table 2.2). Trials were repeated in some areas in different seasons.

Table 2.2 Location and dates of bait-palatability field trials, and details of the mean rainfall, relative possum density and the types of bait tested. Baits tested were 'Mapua' pellet (M), 'No. 7' pellet (7), 'No. 5' pellet (5), and carrot (C) - see section 2.3.2 for further detail.

Trial location (coordinates given in Appendix 1)	Habitat type	Dates	Mean total rainfall for month of trial (mm)	Relative possum population density	Bait types tested
Omihi, North Canterbury	Native scrub gullies/pasture	August 1976 November 1976 February1976 May 1977	74 61 64 94	High	M, C, 7
Deception Valley, Westland	Mixed native hardwood forest on steep hill country	August 1976 November 1976 February 1976 May 1977	391 544 417 437	Medium	M, C, 7
Deception Valley, Westland	Seral vegetation in steep eroded gullies	August 1976 February 1977	391 417	Low	M, C, 7
Bullock Creek, Westland	Mixed hardwood-podocarp forest/pasture margin	September 1976	206	Medium	M, C, 7
Hokonui Hills, Southland	7-year-old *Pinus radiata*	September 1976	66	Low	M, C, 7
Lake Haupiri, Westland	Mixed native hardwood forest on steep hill country	October 1976	323	High	M, C, 7

Trial location (coordinates given in Appendix 1)	Habitat type	Dates	Mean total rainfall for month of trial (mm)	Relative possum population density	Bait types tested
Lake Haupiri, Westland	Lowland podocarp forest/pasture margin	October 1976 December 1976	323 274	Very high	M, C, 7 M, C, 7, 5
Deception Valley, Westland	Lowland podocarp forest/pasture margin	November 1976 May 1977	544 437	Medium	M, C, 7
Lake Haupiri, Westland	Red beech-podocarp terrace forest	December 1976	274	Medium	M, C, 7
Omihi, North Canterbury	10-year-old *Pinus radiata*	January 1977	56	Low	M, C, 7, 5
Harper Valley, Canterbury	Mountain beech forest	February 1977	86	Low	M, C, 7, 5

2.3.2 Bait types tested

In all trials carrot (Manchester Table variety) was used as the reference bait against which other bait types were compared. Carrots (C) used were within 2 weeks of being harvested. They were chopped in a bin into pieces averaging 2-3 cm^3 by the use of a spade with two blades set at right angles to each other. Three types of manufactured pellets baits were used. 'No. 5' and 'No. 7' baits were manufactured at the Wanganui Poison Factory (operated by the Agricultural Pests Destruction Council) by extrusion of a wet mix of pollard and glycerine with molasses being incorporated in the No. 5 and raspberry jam in the No. 7 bait. Lissamine green dye was added to both as a bird deterrent (Kalmbach & Welch 1946; Caithness & Williams 1971). Following extrusion, the material was automatically cut into pellets weighing approximately 5 g on average. 'Type M' pellets were manufactured by Fruitgrowers Chemical Company, Port Mapua, Nelson. This type of bait, for which the formula remained confidential, was of a harder texture than the Wanganui-produced baits, but was of a similar size and was also coloured green. All pellet baits were manufactured within three months before use.

2.3.3 Summary of trial method

The trial method was based on that detailed in section 2.2. For each bait type tested, 15 plots were established by placing a numbered peg in the ground. Plots were spaced 40 m apart on parallel lines separated by 200 m. Bait types were laid singly and in sequences along lines. The same sequence was also followed in laying different bait types at each plot on successive nights until all plots had been used to present each bait type. Sufficient bait was presented at each plot to avoid complete consumption and hence the likelihood of underestimating palatability. Reference plots of baits were established to permit correction of the data for climatic variation. Mean consumption of bait types, expressed as the arcsin% transformed (for normalising data) values of the percentage eaten, were analysed separately for each trial by single-factor ANOVA. To make the results of trials comparable, consumption of pellet baits was expressed relative to the consumption of carrot in all trials. Where an overall significant difference was shown, precise differences were determined at the 5% level by Duncan's Multiple Range test.

2.3.4 Results of palatability trials

Figure 2.1 summarises the results from all trials and indicates where significant differences were detected between bait types. While the unbalanced design of the trials did not permit a factorial analysis of 'region' and 'season', there were clear differences in possums' bait preferences between trials that demonstrated a strong 'region' effect, and lack of a 'season' effect.

Regionally, preferences for particular bait types were quite different, even where habitat type was similar. For example, in mixed hardwood forest at Haupiri, carrot was of significantly higher palatability than pellet baits, whereas at the same time of the year in very similar habitat in Deception Valley, No. 7 pellet was significantly more palatable than type M pellet, and both were significantly more palatable than carrot. Similarly, preferences, during the same season, were found to be markedly different between populations in the pasture/forest fringe areas at Lake Haupiri and in Deception Valley, and also between populations in *Pinus radiata* plantations at Omihi and Hokonui (although these trials were conducted 5 months apart).

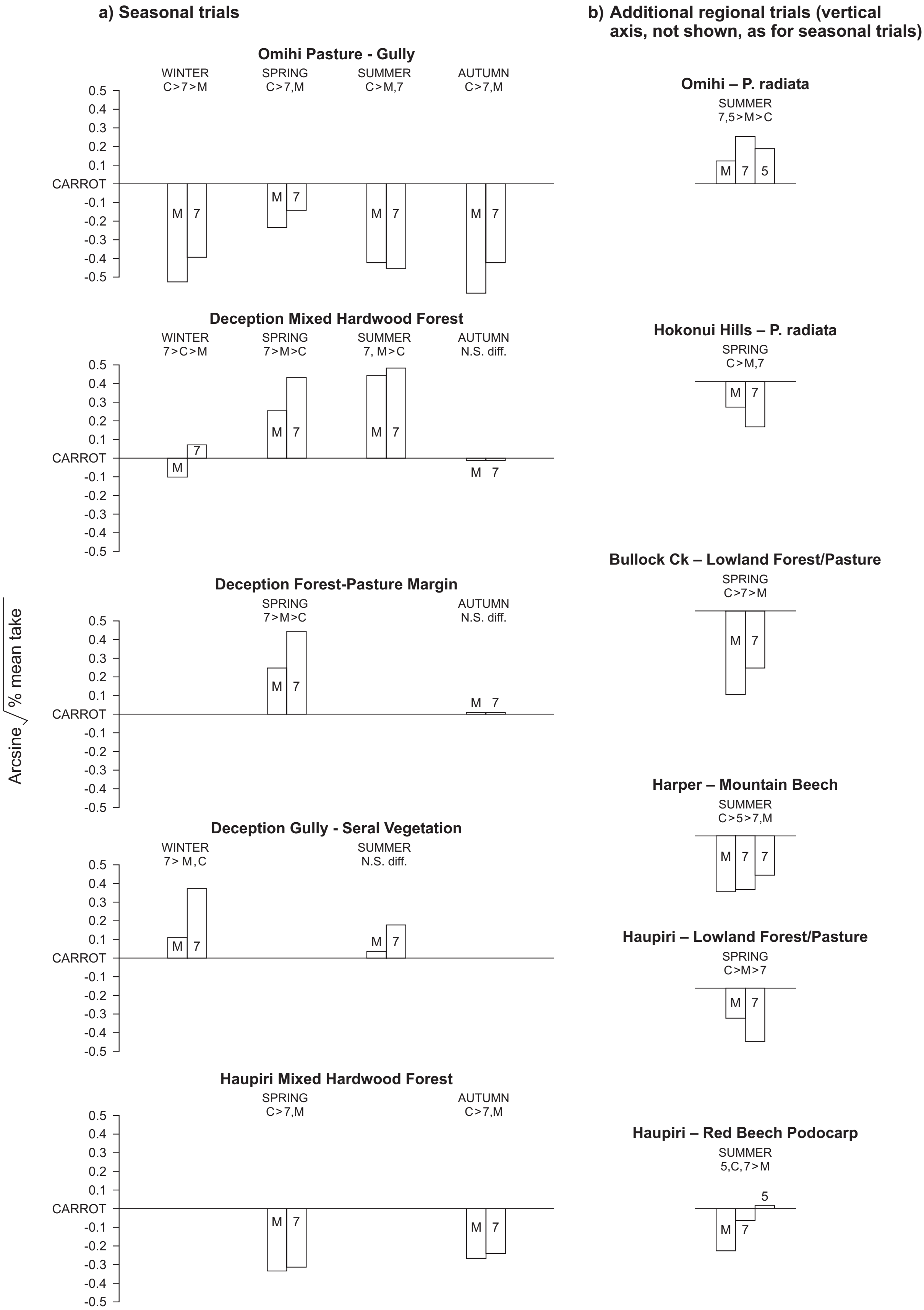


Fig. 2.1 Mean consumption of pellet baits (types 'M', '7', and '5') relative to carrot ('C') in field trials repeated at five locations (a), and in single trials at six additional locations (b). Significant differences within each trial are indicated by '>' at 95% probability.

Seasonally, palatability of bait types remained more consistent within particular areas. For example, at Omihi, carrot was the preferred bait in all seasons, with little difference between the pellet bait types tested. Similarly carrot was of higher palatability to possums in both spring and autumn in the mixed hardwood forest at Lake Haupiri. By contrast, pellet baits were of higher (n=5) or equal (n=3) palatability to carrot in the eight trials conducted in Deception Valley.

Overall, out of the 20 trials conducted carrot was the preferred or equally preferred bait in 14 trials, No. 7 pellets in 10 trials, and Type M pellets in four. No. 5 pellets were equally preferred in two of three trials in which they were used.

2.3.5 Conclusions from palatability trials

The regional variation in palatability of baits to possums was consistent with earlier literature (exemplified above) indicating variation in dietary preference in different regions of New Zealand. Such variation may, at least in part, be genetically determined. In Australia, genetic variations were demonstrated at the population level in the blood sera of 12 populations (Hope 1970). It is possible that dietary preferences among populations of possums in New Zealand may also be partly genetically determined. This view is supported by Williams & Turnbull (1983) who compared the physiology of possums from Lake Haupiri (Westland) and Wanganui. Lake Haupiri possums had a metabolic rate (standardised for body weight) that was slower than the Wanganui possums, a trait that is adaptive in the frequent periods of cool, wet weather which prevent feeding. In contrast, the Wanganui possums exhibited 'water economy' rather than 'nutritional economy' suggesting that genetic traits were selected in the establishment of possum populations in the drier, warmer Wanganui region. Genotyping of regional populations in New Zealand may therefore yield useful predictors of bait preferences.

Although seasonal variation in natural diet of possum populations has been recorded (Gilmore 1967; Jolly 1976), my palatability trials did not show clear seasonal trends across regions. Even though basically only two types of food (i.e. grain-based pellets and carrot) were presented in trials, these are sufficiently different in moisture content that possums' preferences may be expected to change, at least in relation to water availability. Demonstrating the water-value of different bait types, Rowley (1963) showed that in an arid part of Australia during summer, rabbits preferred carrots (which contain approximately 87% water) to oats, probably because they were suffering from water stress. Therefore the similar, and consistent, preference for carrots by possums at Omihi, where weather throughout the four trials was recorded as fine and local running water was absent, suggests that the palatability of baits to possums may also be determined in part by prevailing weather conditions. Similarly, the inconsistencies in bait preference obtained in the Deception region may have been due to short-term weather changes as considerable variation in weather was experienced before and during trials conducted there. Other seasonally determined factors may also have influenced possums' responses to baits, such as the availability of certain naturally occurring foods (Chapter 4), seasonal fluctuations in deterrent plant compounds, and possums' nutritional requirements in relation to seasonal breeding trends.

Despite the clear demonstration of regional differences in the palatability of baits to possums, there was still a need to assess the significance of the results in terms of likely differences in operational effectiveness. The question remained: 'do baits of higher palatability lead to higher levels of bait acceptance and population reduction?' This led to the planning of a series of trials during 1978-80 in which I compared the acceptance of pellet and carrot baits at several locations (section 2.5), preceded by the development of a marking technique for tracing bait acceptance (section 2.4).

2.3.6 Contemporary review of the study and its findings

This study, conducted 25 years ago, contributed significantly to the future direction of both research and management. Firstly, the study revealed variation in the bait preferences of possum populations and this was considered likely to be valuable in the planning of control operations. Recent research has demonstrated an inverse correlation between palatability and the likelihood of possums consuming sublethal amounts of bait (Henderson & Frampton 1999), confirming the value of conducting relatively inexpensive palatability trials before control operations in order to select the most appropriate bait type. Secondly, the palatability trial methodology developed was considered to be a more reliable predictor of preferred bait type than choice-based preference testing, consequently providing more reliable information on the relative palatability of different bait types. This is because choice-based preference methods exaggerate the palatability of the most preferred bait and underestimate that of the least palatable. Thirdly, carrot was shown to be, overall, the most palatable bait type in this study, and more recent comprehensive research on bait palatability has shown carrot to be consistently more palatable than pellet baits in cage trials (although with differences between carrot types) (Henderson & Frampton 1999) and to be more effective in operational use (Henderson *et al*. 1999b).

The study was, however, deficient in some regards. In particular, the effect of region and season on palatability could not be statistically tested and discriminated as the study was not developed as a replicated, balanced design. Logistically, this would have been extremely expensive and time-consuming to achieve. Instead, a pragmatic approach was followed that afforded extensive sampling of possums' bait preference in a variety of possum habitats, and provided clear evidence of regional differences.

2.4 Development of a method for assessing acceptance of baits by possums in the field

Having demonstrated regional variation in possums' preferences for baits, and realising the importance of relating this to likely operational effectiveness, it was necessary to develop a method for measuring the proportion of a population that would eat bait (i.e. 'acceptance'). Three chemical tracers were therefore evaluated as 'bait markers'. As the work has been published (Morgan 1981), an abbreviated form of the paper is presented here.

2.4.1 Introduction

Tracers have been used in several baiting studies (Lindsey *et al*. 1971; Nass *et al.* 1971; Nelson & Linder 1972; Sullins & Verts 1978). They have also frequently been used to study the movements of animals. Comprehensive reviews of the literature on this subject have been given by Taylor & Quy (1973) and Evans & Griffith (1973).

A successful tracer for field use in possum bait-acceptance studies had to:

1. Be effective as a marker for a minimum of 7 days, thus allowing time for capture of a sample of possums after baiting;
2. Not affect the palatability of the carrier bait;
3. Not affect the behaviour of the possum, particularly in relation to feeding;
4. Be inexpensive in large quantities since the proposed field use would eventually involve addition of tracer to several tonnes of bait concurrently.

2.4.2 Materials

Whilst radioisotopes offered the potential of a quantifiable technique (i.e. measurement of the amount of bait eaten) (Spragg & Fox 1974) they were considered to be too hazardous and, like many of the otherwise apparently suitable chemical dyes, too costly for bulk usage.

Three relatively safe chemicals were therefore selected for evaluation as qualitative markers (i.e. for measurement of bait consumption or refusal).

Demethylchlorotetracycline (DMCT) has been a useful tracer in a variety of vertebrates. A single dose was detectable as fluoresence in the mandible of coyotes *(Canis latrans)* for 5 months (Linhart & Gennelly 1967), and in the mandible of laboratory white rats for 6 months (Crier 1970). Other tetracyclines have been used to mark tissues in fur seals (Yagi *et al.* 1963) and fish (Weber & Ridgway 1962). Lissamine green dye was used in poisoning operations against rabbits and possums in New Zealand as a means of deterring birds from eating the carrot bait (Caithness & Williams 1971). Since contaminant stains appear to be persistent, even at the concentration of 0.01% used operationally, it was considered worthwhile evaluating this dye for use as a tracer. Rhodamine B, a red dye that fluoresces orange under ultraviolet light, was selected for evaluation since it has been used successfully in bait acceptance with black-tailed jack rabbits *(Lepus catijotnicus)* (Evans & Griffith 1973), and Belding's ground squirrels *(Spermophilus beldingi)* (Sullins & Verts 1978).

The three chemicals were separately evaluated in terms of their effect on bait palatability and their persistence as tracers. Bait materials to which these chemicals were added were either chopped carrot or a pellet bait manufactured specifically as a possum bait.

2.4.3 Palatability of dyed baits

In order to mark possums effectively it was necessary to find the maximum concentration of each chemical that could be added as a surface coat without impairing the palatability of the bait. This was investigated in three separate trials in each of which three treatments (0.1%, 1%, and 3% wt:wt as a surface concentration) of the pellet bait and a non-treated control were offered to 11 possums kept in a pen measuring 5 x 30 m. The baits were laid out at three plots of each treatment. Twenty baits were laid at each plot and fresh water and other food (apples, silver beet, and turnip) were also offered freely. The total numbers of baits taken were recorded in the mornings and fresh baits laid. The trials were conducted for 3 consecutive nights. Proportions of baits taken were normalised by arcsine transformation and analysed by two-factor (i.e. night : concentration) analysis of variance and the least significant difference (LSD) test.

2.4.4 Persistence of dye-marking

A total of 45 captive possums housed in individual cages (45 x 65 x 45-cm) were used for testing the persistence of the three chemicals over various time periods. Animals were each given one treated bait just before dusk at the beginning of a test. This is the minimum intake of bait that must leave a detectable trace since the poison baiting of possum populations is based on the principle that each bait should contain a lethal dose of poison (Peters 1975). Possums were inspected at various periods after eating the test bait. A high-intensity (7000 W/cm^2) longwave (366 nm) ultraviolet light was used to search for external traces of Rhodamine B and internal traces of both Rhodamine B and DMCT.

2.4.5 Results and discussion

All baits treated with DMCT presented to possums in the palatability tests were eaten, suggesting the compound is tasteless or not unpleasant to possums even at high concentrations. Gross analysis of bone tissue throughout the skeleton failed to reveal any fluorescence under ultraviolet light in animals that were killed at periods of 24, 48, and 72 h after eating treated bait. Microscopic analysis (at magnification x40) of sagitally sectioned teeth from an animal that was killed at 72 h also failed to reveal any fluorescence under ultraviolet light. Since DMCT has been found to fluoresce in bone tissue in such widely different animals as mammals and fish it was surprising that the possum did not show a similar reaction.

The mean quantities eaten of baits treated with Lissamine green (Table 2.3) differed between nights ($F_{2,24}$ = 14.3, $P < 0.001$) due to lower consumption of the 3% treatment (LSD test $P < 0.05$) which occurred after the first night. This suggests that the animals' behaviour is modified by some kind of metabolic feedback rather than by a purely sensory response. If this is so, it would be tempting to accept the 3% concentration as the maximum for bait acceptance experiments, thus increasing the tracer's persistence in or on the possum. However, to allow a safety margin the 1% concentration was selected as the maximum quantity that could be used without affecting bait acceptance.

Table 2.3 Mean numbers of Lissamine green-dyed and non-dyed baits eaten by possums in a 3-night palatability trial.

	Dye concentration (% wt:wt)			
	0.1	1	3	Non-dyed (control)
Night 1	19.9	20	20	20
Night 2	19.3	16.9	9.8	20
Night 3	20	19.9	7.9	19.9

Three of the 12 possums that were each given a single bait carrying 1% Lissamine green were killed 48 hours after eating the bait. Two of these animals showed no trace of green dye on the paws or in the gut contents or gut tissue. In the rectum of only the third animal were faecal pellets dyed greenish-brown. Since this dye appeared to pass through the gut rapidly, the remaining nine animals of the treated sample were conserved for other experiments and the use of Lissamine green as a tracer was discarded.

Rhodamine B had the same effect on the palatability of pellet baits as did Lissamine green. Quantities of bait eaten nightly (Table 2.4) varied significantly ($F_{2,24} = 23.4$, $P < 0.001$) due to lower consumption of the 3% treatment (LSD test $P < 0.05$) which occurred after the first night. As for Lissamine green, 1% was chosen as the safe maximum concentration of Rhodamine B for surface coating baits.

Table 2.4 Mean numbers of Rhodamine B-dyed and non-dyed baits eaten by possums in a 3-night palatability trial.

	Dye concentration (% wt:wt)			
	0.1	1	3	Non-dyed (control)
Night 1	20	19.6	19.9	20
Night 2	18.1	17.6	6.7	19.1
Night 3	18.9	18.9	13.5	19.9

The persistence of Rhodamine B dye was then determined using a group of 21 possums; each was given either a dry or a moistened 1% Rhodamine-dyed bait and individuals were killed at various periods after bait administration. Dye was found to persist in the gut for between 2 and 4 days but fluorescence of the dye under ultraviolet light was not seen in the gut. Dry baits marked the forepaws for 2 days (n = 5), but left no trace after 3 days (n = 2), or 7 days (n = 3). Moistened baits, whether carrot or pellet, marked the forepaws more effectively. All the animals killed after 2 days (n = 3), 3 days (n = 2), 4 days (n = 2), and 7 days (n = 4) still showed detectable traces of dye. Traces were found under ultraviolet light to remain longest as bright orange lines at the proximal end of the claws of the forepaws. This marking is caused by the possum's habit of manipulating small food items with its forepaws while sitting on its haunches to eat. Since it was later found that the field-use of Rhodamine B dye at 1% concentration would be rather expensive, a similar test was conducted to determine if halving the rate of application of the dye would still produce effective persistence. Thirteen possums, comprising those conserved after Lissamine green testing and four additional animals, were each given a single, 0.5% Rhodamine B-dyed, moist, carrot bait and were killed 7 days later. All 13 showed fluorescent traces of the dye on the paws and around the mouth under ultraviolet light and several still showed visible red stains on the paws under normal light.

Although the use of Rhodamine B as a tracer does not permit determination of the quantity of bait an individual animal has eaten, some measure of this can be obtained by inspecting gut contents. This should be done if only faint traces are found on the paws of an animal known or thought to have consumed bait recently (i.e. 1 or 2 days previously) as this may be evidence of less than a whole bait having been eaten. A small quantity of Rhodamine B left by only one or two bites of a bait will initially leave only a localised stain amongst the stomach contents and later turn the contents of the intestine red-brown. Consumption of an entire Rhodamine B-dyed bait is sufficient to leave a large diffuse stain amongst stomach contents and later colour the contents of the colon and rectum a reddish-purple.

Rhodamine B was selected on the basis of these results as being a satisfactory tracer for determining acceptance of bait by possum populations if dyed baits are moistened before use.

2.4.6 Contemporary review of the study and its findings

Following this study, the Rhodamine B bait-marking method became established as a useful procedure in both research and management. Having selected a bait type for operational use (possibly with the aid of palatability trials), managers are advised to conduct a Rhodamine trial before major aerial control operations as an insurance against costly failure (Henderson *et al.* 1999b). The method was also used as the basis for assessing seasonal variation in bait acceptance (see Chapter 4).

While the method described here has the disadvantage of providing only qualitative data (i.e. 'accept' or 'refuse'), recent work by Fisher (1998) has demonstrated that rhodamine 'bands' appear in hair after mammals consume dyed bait. Since the bands 'move' as the hair grows, this offers a potential way to estimate the time since baits were eaten, and measurement of fluorescence intensity may indicate the amount of bait eaten. Such a temporal and quantitative marker would be of value in predicting non-target responses to baits as well as assessing likely operational success. Research is currently underway at Landcare Research to develop the use of rhodamine in this way (P. Fisher, pers. comm.).

The failure of DMCT to provide fluorescence was suprising given its effectiveness in a wide range of other animal groups. This suggests that either possums (and perhaps all marsupials) metabolise the compound very differently compared with other animals, or, the material used may have become inactive despite being stored in a fridge. Since tetracyclines have been shown to cause fluorescence in animals as diverse as fish, seals and rats, it appears unlikely that marsupials metabolise tetracyclines in a different (non-fluorescing) manner. It would therefore be worth repeating tests with freshly supplied DMCT, especially since it was previously found to be a long-lived marker in other species (see 2.4.2). A long-lived, 'broad-spectrum' marker would be a useful tool in assessing bait consumption by non-target species, particularly under newly emerging control strategies that use long-life baits for maintaining continuous control of possum populations (Morgan 2005 in press). Use of long-life baits may present higher risks to non-target species than conventional baits (because of the longer period of potential exposure) which would be impossible to assess reliably with short-term markers such as Rhodamine B.

2.5 Bait acceptance field trials

The work conducted on bait acceptance trials between 1978 and 1980 has been described in detail elsewhere (Morgan 1982). An abbreviated form of the paper is presented here.

2.5.1 Introduction

With the development of a technique for monitoring bait acceptance completed, I commenced a series of bait acceptance trials in the field, starting in 1978. The aim of these trials was to determine how well palatability trials predicted the likely uptake of bait (and hence likely operational effectiveness) in the field. If palatability trials were found to be good predictors of bait acceptance, they could be used as a simple, inexpensive management technique for bait selection.

2.5.2 Methods

Non-toxic bait acceptance. Five trials (Table 2.5) were conducted to determine the proportion of possums eating different types of possum bait (i.e. bait acceptance). As well as testing type M and 7 pellets (see section 2.3.2) and carrot on separate blocks, in each trial a mixture of the three bait types in equal proportions was tested on a fourth block. All baits were treated with 0.1% Rhodamine B marker dye leaving baits with a moistened surface for more effective marking. Baits were distributed by helicopters with underslung sowing buckets at rates estimated to deliver 0.5 bait/m^2 (i.e. a high application rate, equivalent to 32.5 kg/ha of type 7 pellets, that would ensure possums encountered the bait). Two nights were then allowed for possums to feed on baits, and over the next 5 nights an intensive effort was made to capture possums using both lured cyanide paste and non-lured, concealed leg-hold traps. Since exactly the same proportion (58%) of both the bait acceptors and refusers were caught by poison (rather than by traps) over all trials, there was no indication that capture by cyanide poison was biased towards bait acceptors.

Table 2.5 Location, date, habitat type, bait types tested, population density and size of blocks in five bait acceptance trials. Baits tested were 'Mapua' pellet (M), 'No. 7' pellet (7) and carrot (C) - see section 2.2.2 for further detail.

Trial location (coordinates given in Appendix 1)	Date	Habitat type	Bait types tested	Population density (possums/ha)*	Block sizes
Lake Haupiri, Westland	Winter 1978	Rata-kamahi forest	M, 7, C, & mixture	7	20
Taipo Valley, Westland	Spring 1978	Rata-kamahi forest	M, 7, C, & mixture	1.5	40
Kaingaroa Forest	Summer 1979	Pinus radiata (7 years old)	M, 7, C, & mixture	1.5	50
Kaingaroa Forest	Winter 1979	Pinus radiata (7 years old)	M, 7, C, & mixture	1	50
Taramakua Valley, Westland	Summer 1980	Rata-kamahi forest	M, 7, C, & mixture	2.8	30

* Assessed by proportion from 'trapping-to-extinction' density estimate at Haupiri of 7 possums/ha (Coleman *et al.* 1980) on the basis of equal trapping effort in all study sites.

Toxic bait acceptance. During 1979, acceptance of toxic carrot bait was investigated in Westland. Three experimental blocks, each of 100 ha, were located on broad ridges on the east side of Wainihinihi Creek, a tributary of the Arahura River. The large block size was selected because the treatments of toxic bait were expected to reduce population densities. The treatments applied were carrot with 0.2%, 0.1% and 0% (i.e. non-toxic) 1080.

All animals were classified as either bait 'acceptors' or 'refusers' after searching their forepaws, snout, mouth and gut for Rhodamine B dye. Where no evidence of dye was found, forepaws were later inspected under high-intensity (360 nm) ultraviolet light. A 5-m radius around each dead animal was searched for baits to ensure that it had been exposed to bait. The small proportion (4.8%) of possums captured in non-baited 5-m radii, and juvenile animals, still dependent on their mothers, were excluded from the data set. Results from the five non-toxic bait acceptance trials were analysed by two-factor analysis of variance (i.e.

population : bait type), and where overall significance occurred, pairwise comparisons were made by Duncan's Multiple Range Test.

All animals were sexed and aged by counting cementum layers of molar teeth (Clout 1977). Each animal was weighed and measured to determine mean condition by developing weight/length equations for each population from linear regressions of the natural logarithms of body weight (W) in grams (to the nearest 50 g) and total length *(L)* in centimetres (Bamford 1970). The relationship is thus of the form $W = aL^b$, or $\log_e W = b \log_e L + \log_e$ where a is a constant. The slope (b) of each regression is an index of the mean growth characteristics of the population (Taylor 1979) and it is used here as a relative index of population condition. The use of slopes as an index has been used in the assessment of population condition for other species including shrimps (Prasad 2001) and fish (Overton *et al*. 2003), This method was used rather than that given by Bamford (1970) who's focus was seasonal change within populations, and which required that quaterley samples be collected as a basis for assessing change in the weight:length ratios of individual possums relative to their predicted average value.

Challies (1973), in assessing condition of deer populations, showed that season of sampling and differences in population age structure and sex ratios may all affect such assessment. In this study, comparison of populations at different times of the year was deliberate and hence seasonal effects may well be combined with the other environmental parameters that determined condition of the different populations. Since young animals are more sensitive to environmental fluctuations than adults, animals of less than two years of age were removed from the analysis as a likely source of heterogeneity. Population sex ratios were found by chi-squared test to differ significantly ($P < 0.05$), and so slopes were calculated separately for the sexes, and a weighted mean slope then calculated for each population. Analysis of covariance was used to develop the regressions and test for variation in population slopes, and Duncan's Multiple Range Test for unequal replications (Steel & Torrie 1960) was used to rank the weighted mean slopes and further analyse the differences.

2.5.3 Results

Non-toxic bait acceptance. In the Haupiri and Taipo trials, virtually all animals ate non-toxic bait, regardless of the type encountered; very high percentages (>90%) accepted bait in the Kaingaroa winter and Taramakau trials; but only moderate percentages (49-80%) in the Kaingaroa summer trial ate bait (Table 2.6). Acceptance was significantly lower (P <0.01) in the Kaingaroa summer trial than in all the others (which were statistically similar), and overall, there was no significant difference in acceptance of the four bait treatments ($F_{3,19}$ = 0.39, P = 0.76).

Table 2.6 Numbers of possums caught (n), numbers marked (R+), and percentage marked (%) in five bait acceptance trials. Baits tested were 'Mapua' pellet (M), 'No. 7' pellet (7) and carrot (C) – see section 2.2.2 for further detail.

Baits tested	Haupiri (winter)			Taipo (spring)			Kaingaroa (summer)			Kaingaroa (winter)			Taramakau (summer)		
	n	R+	**%**	n	R+	**%**	n	R+	**%**	n	R+	**%**	n	R+	**%**
M	98	98	**100**	52	50	**96**	30	24	**80**	35	34	**97**	96	95	**99**
7	157	157	**100**	78	77	**99**	55	46	**84**	25	25	**100**	40	38	**95**
C	116	116	**100**	22	22	**100**	52	30	**58**	70	64	**91**	81	74	**91**
Mix	78	78	**100**	43	43	**100**	35	17	**49**	25	23	**96**	39	39	**100**
Total	449	449	**100**	192	192	**98**	172	117	**68**	154	146	**95**	256	246	**96**

A detailed demographic analysis of the data was not possible, nor in fact necessary, due to the low proportions of animals refusing bait in all but one of five non-toxic trials. A higher percentage of females (7.2%) than males (4.6%) refused bait (χ^2 = 3.5, P = 0.06), but the percentages of young possums (6.5%) (i.e. less than two years old) and older possums that refused bait were similar (χ^2 = 0.55, P = 0.55).

Toxic bait acceptance. Virtually all possums (98%) at Wainihinihi Creek ate carrot in the non-toxic treatment block, as found in other Westland trials (Table 2.7). Assuming the population density of these three treatment blocks was the same, the numbers of animals caught on the 0.1% 1080 and 0.2% 1080 treatment blocks suggest that around 32% and 17% respectively of the populations survived. From the two toxic treatments, 41% of the survivors showed some evidence, usually very slight, of Rhodamine B dye indicating that they had survived a sublethal intake of bait. The remaining 59% of the survivors showed no evidence of the dye and so apparently refused to eat the bait altogether, even though they must have encountered bait (since its distribution was similar to that in the non-toxic treatment block).

Comparing the data from the two toxic treatment blocks, proportionately more animals survived by refusing to eat carrot in the 0.2% treatment area than in the 0.1% area. Of the animals that survived after eating toxic bait, none of those captured in the 0.2% treatment area were estimated to have eaten an entire average-sized bait (this assessment is described in Morgan (1981)).

Table 2.7 Summary of the results of the Wainihinihi Creek toxic bait acceptance trial showing possums caught (n) and marked (R+); the percentages of populations surviving (S%), the percentage of survivors eating more than one carrot bait (S+%) or eating less than one carrot bait (S-%), the percentage of survivors refusing carrot (R%), and the percentage of the total population eating carrot (C%).

Carrot bait treatment	n	R+	S%[1]	S+%	S-%	R%	C%[2]
Non-toxic	94	92	100	98	0	2	98
0.1% 1080	30	17	32	17	40	43	86
0.2% 1080	16	4	17	0	25	75	87

[1] Assuming equal population densities prior to poisoning and equal catch efforts in each treatment block

[2] For toxic treatments, this is the sum of the percentage killed by toxic bait and the percentage of the population surviving that was marked. That is: C% = (100-S%) + (S% * ((S+% + S-%)/100)

Condition, considered separately for both sexes, was found to differ significantly between populations (Table 2.8). Both the summer and winter populations at Kaingaroa were in better condition than the Westland populations. Surprisingly, the possums caught in winter at Kaingaroa were in significantly better condition than those caught in summer.

Table 2.8 Weighted mean slopes of loglength/logweight regression for possum populations in the six trial areas, ranked from poorest to best condition. Kaingaroa (winter) > Kaingaroa (summer) > Haupiri > Taramakau > Taipo > Wainihinihi (P = 0.05).

Population	Weighted mean slope
Haupiri	2.788
Taipo	2.182
Kaingaroa (summer)	3.006
Kaingaroa (winter)	3.092
Taramakau	2.676
Wainihinihi	1.732

2.5.4 Conclusions from acceptance trials

Poor success in many poisoning operations during the 1960s and 1970s led forest managers to assume that a major cause for failure was that some possums simply did not like the (non-toxic) bait material. Consequently, a considerable effort was devoted to producing more palatable baits, as described in Chapter 1. The results from these bait acceptance trials show that dislike for the non-toxic bait material is unlikely to be the major cause of failure in most winter poisoning operations.

The first trial at Haupiri produced a very clear result from a large sample of animals. All 449 possums caught in the vicinity of baits had eaten some. The moderately high density of 7.0 possums/ha may well have intensified competition for food in this population, thus explaining the complete acceptance of bait. High levels of bait acceptance were also found in the Taipo and Wainihinihi populations, in trials conducted in winter and spring respectively. Although both populations were at low density, the relatively poor condition of the animals indicates a poor nutritional plane which may have predisposed them to accept bait.

Only in the Kaingaroa summer trial was there a significant proportion of the population that did not eat the non-toxic bait offered. The Kaingaroa population was typical of the low-density, relatively high condition populations found in pine plantations (N. Gibbs, fur buyer, pers. comm.). In such habitats population density is most probably controlled by the availability of nest sites rather than food. Although the diversity of food sources was less than in most other habitats (Warburton 1978), many of the plants, such as pine pollen, bracken, tutu *(Coriaria arborea)* and a variety of grasses, are highly nutritious (Clout 1977). Thus, as expected, the Kaingaroa population showed the poorest level of bait acceptance, especially in summer (when Bamford (1970) found possums in Westland to have good body condition). The winter trial conducted at Kaingaroa was designed to show if the population would be more inclined to accept bait in winter when natural food supplies are less nutritious. Overall, the percentage of animals there accepting bait increased from 68.4% in summer to 94.8% in winter, although body condition in winter was found to be highest of all six populations, in contrast to the lowest 'seasonal' condition reported in late winter by Bamford (1970).

Because the Kaingaroa summer trial had yielded such an interesting result, a further trial was conducted in summer with a low-density population in Taramakau Valley, Westland. This population had been maintained at low density, not by lack of nesting sites, but by habitat deterioration caused by the formerly high possum densities, poisoning by the NZ Forest Service in 1961, and sustained commercial hunting. During late summer, it was expected that this population would be in peak condition (Bamford 1970) but it was, in fact, only of average condition. Although 96% acceptance of all bait treatments was extremely high, approximately 9% of animals refused to eat carrot bait, as was also found at Kaingaroa in winter. Though carrot bait was not found to differ significantly from other bait types overall ($P = 0.76$), these findings suggest that pellet baits, as suggested by palatability trials, may in some situations be marginally more acceptable than carrot bait.

In considering the predictive value of population density and condition, Batcheler *et al.* (1967) suggested that where population density is 5 possums/acre (i.e. 11/ha) or less, then kills of 90% or more are unlikely. The results of these trials show that acceptance of non-toxic bait by more than 90% of the population can be expected even when animal density is very low (i.e. <2 possums/ha). Condition, which reflects the combined effects of all environmental stresses, was shown by Batcheler *et al.* (1967) to be negatively correlated with poisoning success. This is consistent with the poor bait acceptance recorded by Kaingaroa possums in good condition in summer, but inconsistent with the high level of bait acceptance recorded by Kaingaroa possums in good condition in winter. If condition is to be useful generally as a predictor of poisoning success, I believe a more precise indication of animal condition is required for assessing current welfare. Depletion of fat reserves and consequent changes in length/weight relationships may be expected to lag behind changing environmental conditions, and this was indeed so at Kaingaroa. A more immediate measure of environmental stress, and hence predictor of bait acceptance, may be changes in weight of the thymus gland (Ozoga & Verme 1978) but this has not been tested in possums.

An indication of why some possums survive aerial poisoning operations is given by the results of the Wainihinihi Creek trial. There, non-toxic bait was eaten by virtually all animals that encountered it, reaffirming the evidence from non-toxic bait trials that conventional bait materials are generally acceptable to possums. Where 1080 baits were distributed, an average of 25% of populations survived, and of these, 41% had survived a sublethal dose, as indicated by traces of Rhodamine B dye within the gut. These animals must have survived for one of two reasons. Firstly, they may have found the toxic bait unpleasant to taste by virtue of the 1080 poison, and hence only nibbled the bait; or they may have encountered a sublethal bait, eaten it, and lost their appetite before encountering other baits. The majority of survivors (i.e. 59%) from the two blocks where toxic carrots were sown showed no evidence of having eaten bait. Since they are assumed to have encountered it, refusal appeared to result from an aversion to the bait by sense of smell. In support of this argument the results show that a higher proportion of refusers were caught in the area where the 1080 concentration on bait was higher. However, the greater proportion of possums surviving through olfactory aversion in the 0.2% treatment area is also enhanced by fewer animals surviving after eating small quantities of the more toxic bait.

There remains the possibility that possums survive poisoning operations because they never encounter bait. Although great effort was made to distribute baits evenly and accurately in these trials, records made during the capture of possums showed that of 1367 animals caught, 66 (4.8%) were caught at sites where no bait was found within a 5-m radius. In many instances unbaited areas of much larger radius were obvious. In routine operations where the pilot is often unfamiliar with the target area, the distribution of baits would be even less uniform. Furthermore, since fixed-wing aircraft, with their larger capacities and cheaper operating costs, are normally used, their poor manoeuverability compared with helicopters compounds the difficulty of achieving effective sowing.

There is also a possibility that some animals may spend very little time on the ground (Ward 1979) and hence be less likely to encounter toxic baits. The trials did not assess this, but it could be significant depending on the habitat type and distribution of food plants. I suspect that such animals would not differ in their response to bait compared with those that use the ground. However, if some individuals are mainly tree-dwelling, it will be necessary to develop potent lures to attract them from the canopy to baits on the ground, or alternatively, to develop long-lived baits that will eventually be encountered by such possums.

These results lend support to the normal practice of conducting aerial control operations in late winter when the animals are expected to be in poorest condition. Provided that one of the bait types tested in this study is used, acceptance of non-toxic bait would be expected to be very high even in low-density populations. However, the study suggested that 1080 poison deters many possums from eating a lethal, or any, quantity of bait.

2.5.5 Contemporary review of the study and its findings

This study was valuable in identifying some important factors that contributed to operational failures. Firstly, the findings shifted contemporary thinking beyond questions of bait palatability towards possible problems with the 1080 poison (i.e. aversiveness, appropriate concentration, and effect of bait size on dose) as factors that may be important in influencing the effectiveness of most operations. In fact results of the first trial, at Lake Haupiri, strongly suggested that the differences in bait palatability recorded in earlier trials at the same location (see section 2.2) could not be accepted as accurate predictions of likely bait acceptance. However, the relatively poor acceptance recorded at Kaingaroa in summer was the first experimental evidence that baiting operations may occasionally be unsuccessful. Speculatively, this was attributed at the time to the abundance of natural foods available; this possibility has been examined in depth in a later study (Chapter 4). For most operations, however, it appeared that differences in bait palatability may be relatively unimportant when compared with the possibility that the poison itself may deter possums, as was strongly suggested by the Wainihinihi Creek trial.

A second factor that emerged from the study as a likely contributor to possum survival was the failure of some possums to encounter baits due to gaps in coverage. This led me to conduct a number of field surveys of bait-distribution to better quantify the extent of the problem, and to then collaborate with aerial operators in using navigational guidance sytems to help reduce the problem (Chapter 3).

Thirdly, the study raised the prospect that possums living predominantly in the canopy may also fail to encounter bait. Radio-telemetry showed that only 4-19% of 'active' time was spent on the ground among four possums monitored in mixed broadleaf-podocarp forest for 2 years (Ward 1979). Later efforts to sample such possums proved very difficult, but of five possums shot in the forest canopy during bait acceptance trials at Puketi Forest, Northland, three were unmarked: this was a significantly higher proportion than those captured at ground level (17% unmarked out of 125) (Morgan 1994b). Further data are required as it is likely that this remains a reason for possums surviving despite the improvements in control practice that have been introduced. Compounding the problem is new information which shows that the likelihood of survival increases if rain falls soon after aerial baiting, because pellet baits become less palatable 2 days after becoming damp (Henderson & Frampton 1999) and 1080 is leached out of pellet baits rapidly (Bowen *et al.* 1995). Carrot bait does not suffer these disadvantages and is therefore better suited to aerial control operations during periods of unstable weather (Bowen *et al.* 1995). 'Long-life' baits are now being developed (e.g. Morgan 2003) that are expected to remain palatable and toxic for long enough that they will eventually be encountered by possums living either in the canopy or gaps at the time of control.

A further important finding of the study was the suggestion that aerial baiting could be very effective among low-density populations (c.f. Taipo and Taramakau trials) which, today, are increasingly becoming the norm (but nevertheless still requiring control). This challenged the prevailing view that possums in such populations were less likely to eat baits (Batcheler *et al.* 1967; Bamford & Martin 1971). Furthermore, my data were not completely consistent with the prediction that poorest condition occurs in winter (Bamford 1970) and that this leads to greatest poisoning success (Batcheler *et al.* 1967). A high level of bait acceptance was recorded in winter at Kaingaroa when condition was (unexpectedly) highest of all trials. Therefore, my findings in relation to population density and condition suggest that other 'seasonal' factors may be involved in determining operational success. Chapter 4 describes the research I carried out to further investigate the effect of food availability on likely poisoning success, and discusses the possible effect of temperature on success.

Chapter 3. Improving the Effectiveness and Efficiency of Aerial Sowing of Baits for Possum Control

3.1 Introduction

In this chapter, I summarise and review past research that I conducted during 1985-96 on improving aerial sowing of possum baits. While observing aerial control operations in Westland during the late 1970s, I noticed that, at times, no baits were found throughout large areas of forest within target areas. Although this was not widely recognised at the time, it was not surprising given that coverage of target areas was dependent on the flying skill of pilots who used only map-reading, memory, compasses and altimeters for navigational guidance. Potentially, therefore, it appeared that some possums may have survived aerial control operations because they failed to encounter baits due to incomplete coverage. Possums living in 'gaps' at the time of baiting could be killed only if they moved into a baited zone before bait had deteriorated or before it had been eaten by other animals. The importance of regular bait distribution in achieving effective aerial control of rabbits had already been identified by Godfrey (1973), who attributed the occurrence of gaps in bait distribution to the uneven flow of baits of irregular size and shape.

Another aspect of aerial sowing, which directly affects the cost-effectiveness of control operations, is the sowing rates for bait. This assumes particular importance where pellet baits costing about \$2500 per tonne are being distributed. Prior to the research described in this chapter, the sowing rates used in routine control operations varied between 5 and 40 kg/ha. This variation was considered necessary to cater for differing densities of both the target population and the understorey tier of vegetation, which could conceal bait or prevent it from reaching the ground. Even so, such rates often far exceeded the biomass of possums in the control area, and were primarily dictated by the highly variable size and toxin content of baits rather than by target population density (Batcheler 1982). Baits that were too small could have induced sublethal poisoning (Batcheler 1978) and baits containing excess 1080 could have been rejected by possums detecting the 1080 poison (Morgan 1990a). Improvements were made in the quality of bait in the 1970s and 1980s (Batcheler 1982) leading to the adoption of quality standards as described in Chapter 7. These improvements increased the probability that possums would encounter palatable and lethal baits and, consequently, it became appropriate to investigate the feasibility of reducing sowing rate without reducing operational effectiveness.

This chapter describes research that I carried out to address deficiencies in the aerial delivery of possum baits. Specifically, the studies aimed to:

- measure the coverage and kill achieved during aerial control operations (section 3.2)
- simulate aerial baiting in the field to determine the effect of gaps and different sowing rates (section 3.3)
- assess the value of navigational guidance systems (section 3.4)
- determine the minimum sowing rate required for effective control (section 3.5).

This work has been published fully in a number of papers (Morgan 1994a, b, and c; Morgan *et al.* 1996a and b; Morgan *et al.* 1997) and unpublished reports (Morgan 1990b; Morgan & Warburton 1987; Thomas & Morgan 1996). Studies described in sections 3.2, 3.4, and 3.5 were essentially 'research by management' exercises in which normal management operations using different methods were monitored. They are summarised here to demonstrate the improvements made in maximising the likelihood of possums encountering baits sown at optimal rates. Section 3.3 was a controlled experiment that permitted more precise assessment of aerial sowing treatments and confirmed some of the empirical findings of the other studies: accordingly, it is presented in more detail.

3.2 Effect of coverage on kill during aerial operations

I conducted my assessment of coverage, and its likely effect on kill, by recording what was typically achieved in routine aerial sowing operations.

3.2.1 Methods

Bait coverage and possum kill were monitored after seven aerial control operations conducted at seven locations between 1985 and 1991 (Morgan 1994b) (Table 3.1). The dispersion of baits on the ground following aerial sowing by a variety of aircraft was measured by searching for baits along a series of 2-m-wide transects 100-200 m apart and orientated at 90˚ to the direction of flight paths. When no baits were seen along the transect for more than 20 m, the starting distance (measured by hip-chain) and length of the gap were recorded. Diagrams of coverage were drawn by interpolating recorded gaps along adjacent lines and percent coverage was calculated after digitising treated and non-treated areas. Where gaps in lines did not clearly link, an approximation of the total coverage was made by calculating the mean percentage of each line, in 20-m segments, that was baited.

Possum kill was assessed from the reduction in faecal pellets accumulating on plots, from changes in the number of possums seen in spotlight counts, or from changes in the numbers caught in leg-hold traps before and after poisoning (Baddeley 1985).

3.2.2 Results

All aerial sowing operations monitored between 1985 and 1991 suffered incomplete coverage, which varied from 52 to 82% (Table 3.1).

Table 3.1 Bait coverage and possum kill in aerial control operations where navigation guidance systems were not used.

Location of operation (coordinates given in Appendix 1)	Bait sowing rate (kg/ha)	% coverage	Maximum recorded gap width (m)	% kill
Granite Hill, Westland, block 1	15	59.5	180	64.4
Granite Hill, Westland, block 2	15	76.0	200	73.3
Granite Hill, Westland, block 3	15	51.6	210	69.8
Copland Valley, Westland	20	51.9	170	62.0
Pureora Forest, Waikato	10	79.0	210	80.0
Slopedown Forest, Southland	9	70.0	194	86.0
Waipoua Forest, Northland	5	82.0	400	86.0

As an example of the coverage that was typically achieved, Figure 3.1 shows the extent and distribution of gaps that were found in a randomly selected part of the 2800-ha area treated at Pureora Forest in 1987. Amongst other operations, poor coverage was obtained at Granite Hill (52% in block 3) and in the Copland Valley (52%), and the best overall coverage achieved was 82% at Waipoua Forest. The average coverage obtained in the seven operations monitored was 71%.

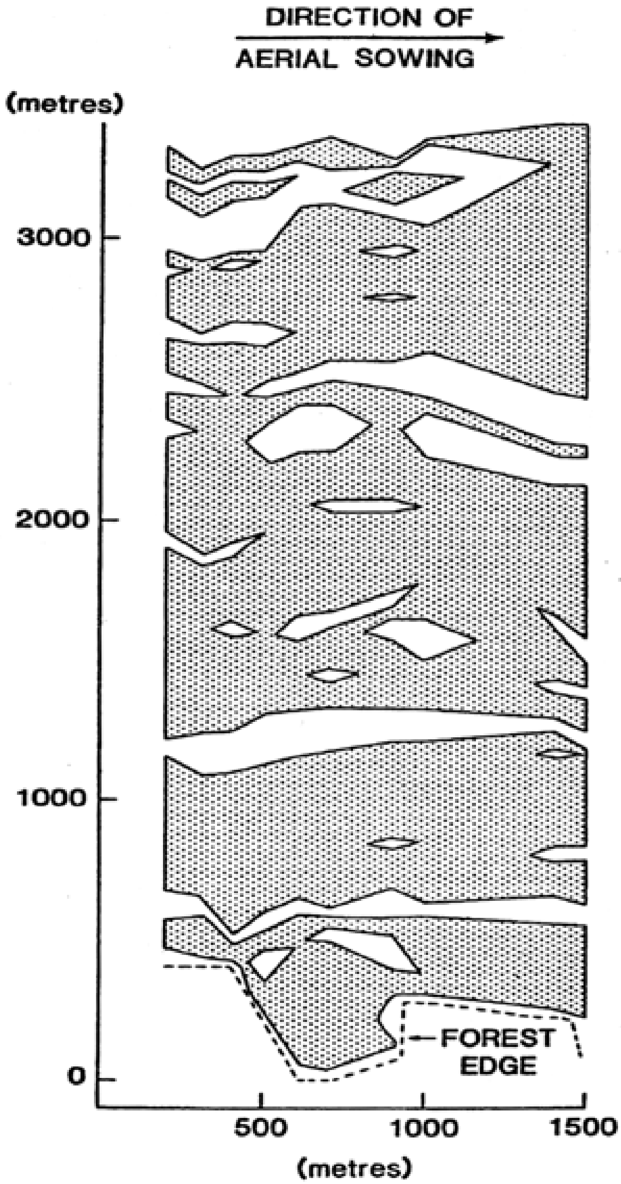


Fig 3.1 Coverage (shaded) of a randomly selected part of Pureora Forest aerially sown with 1080 baits by fixed-wing aircraft in May 1986. Coverage of 79% of the block was recorded, and a kill of 80% was achieved. (From Morgan & Warburton 1987).

Maximum gaps between sowing swaths of 170-240 m were recorded in all operations except at Waipoua, where a gap of 400 m was recorded. Major gaps usually extended across the full width of the surveyed blocks and presumably, therefore, beyond the block boundaries.

Data from the seven operations showed that kill was correlated with coverage (r = 0.80, P = 0.03) (Fig. 3.2). Assuming that bait sown is of good quality and sowing is followed by a period of at least two fine nights, the data predict that if 70% of the area is sown with baits, a kill of 76% can be expected, but if complete coverage can be achieved then the kill will increase to 94%. The small percentage of possums (around 6%) predicted to survive from this correlation are most probably those that had a low preference for baits or were living in the canopy (section 2.5.4), or were 'neophobic' towards baits (section 5.1).

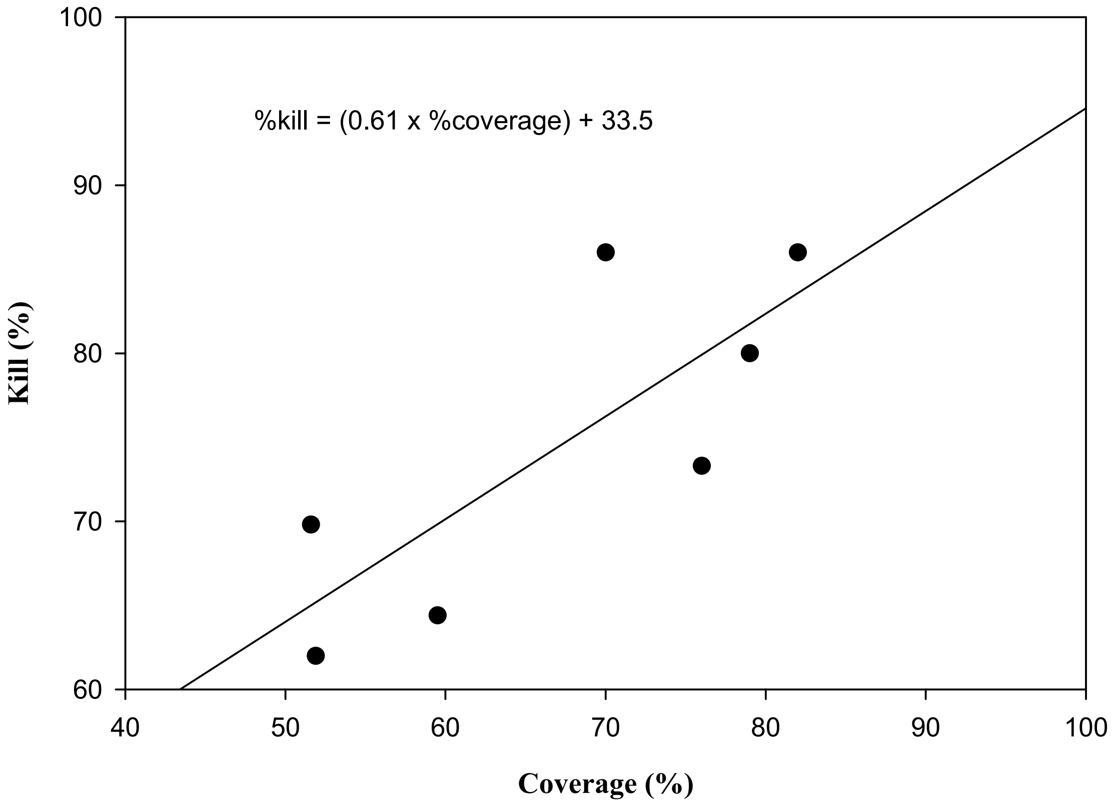


Fig 3.2 Correlation between coverage and kill in seven aerial control operations monitored between 1985 and 1991 (i.e. before the use of aerial navigation guidance systems). (From Morgan 1994a).

3.3 A field simulation of aerial control to assess the effect of gaps and variable sowing rate

To further illustrate and confirm the conclusions drawn from monitoring coverage and kill in routine operations, I conducted a controlled field experiment in June 1985 (Morgan 1994c) to determine whether pilot inaccuracy affected bait distribution even under optimal conditions, whether deliberately-created small gaps in bait distribution affected availability of baits to possums, and whether cost-effectiveness could be improved by sowing less bait. Non-toxic dyed baits were used so that possums could be captured, and bait acceptance (i.e. the proportion of possums that ate bait) was assessed as the measure of sowing effectiveness.

3.3.1 Methods

Study area. An experimental area was selected in Waimihia State Forest, an exotic forest 15 km south-east of Taupo (see Appendix 1 for coordinates). The site was chosen for its abundant possum population (thought to be at least 10 possums/ha), flat terrain, and open forest structure with many obvious compartment boundaries. Conditions were therefore optimal both for ease of aerial sowing and for sampling possums. The homogeneous habitat of the study site was considered an additional advantage in minimising the effects of extraneous random variation on experimental comparisons. Four similar blocks (97-134 ha) were chosen of 12-year-old *Pinus radiata*, growing on pumice soils with sparse understorey vegetation, and delineated by roads and tracks.

Bait materials and sowing strategies. Non-toxic 'Mintech' pellet baits (Fruitgrowers Chemical Company, Mapua) were coated with 0.5% (wt/wt) Rhodamine B dye to indicate bait consumption as described in Chapter 2. The mean weight of baits and uniformity of bait size were assessed by weighing 500 randomly sampled baits. Baits were distributed from a hydraulically-operated sowing bucket carried beneath a Hughes 500D helicopter. All flight paths were orientated directly north or south.

Baits were distributed differently in the four blocks (Table 3.2). Block 1 was treated conventionally – complete and uniform coverage of the block at a rate of 5 kg/ha was attempted by the helicopter pilot with no special navigation aids. Block 2 was treated with 100-m swaths of bait, also sown at 5 kg/ha, but with 100-m-wide untreated strips between the sown swaths. The ends of flight lines were marked by helium-filled balloons floated above the canopy at 200-m intervals along two parallel boundaries of the block. Blocks 3 and 4, also with marked flight paths, were treated with lower (3kg/ha) and higher (10 kg/ha) sowing rates, respectively.

Table 3.2 Bait sowing strategies at Waimihia State Forest. Baits were sown in a swath 100 m wide at rates and coverage as indicated.

Block	Area (ha)	Sowing rate (kg/ha)	Sowing treatment	
			Coverage	Flightpath marked
1	118	5	Complete	No
2	134	5	Alternate	Yes
3	97	3	Complete	Yes
4	110	10	Complete	Yes

Sowing rates were established using the formula (derivation given in Morgan 1994c, and section 7.3.1):

$$\text{Sowing rate (kg/ha)} = \frac{\text{Output rate (kg/min)} \times 600}{\text{Flying speed (km/hr)} \times \text{swath width (m)}}.$$

The sowing swath width was measured by distributing pellets from the air over an area of bare ground at a fixed height of 30 m (i.e. the normal operational altitude for aerial sowing of possum baits). Bait output from the sowing bucket, operating on the ground, was established at two aperture settings. A known weight of pellets was placed in the bucket and the time for this material to be distributed was recorded by stopwatch. The aperture settings selected gave the predicted sowing rates of 5 and 10 kg/ha at a constant flying speed of 90 km/h. The sowing rate of 3 kg/ha was achieved by maintaining bait output as for the 5 kg/ha rate, but increasing the flying speed to 150 km/h.

Measurement of bait dispersion, density, and bait-free areas. After baits had been sown, their dispersion and density on the ground were assessed by sampling transects at 90^o to the direction of the sowing swaths (east-west). Transects were 1 m wide and were divided into 20-m segments to provide a sampling unit of 20 m^2. All baits found were recorded for each segment. Statistical analyses of these data were designed to show the degree of uniformity or randomness of the bait dispersion by fitting the negative binomial distribution, using the chi-squared goodness-of-fit test (Sokal & Rohlf 1973) and calculating 'k' values as indices of aggregation (Southwood 1966). Values of 'k' above 8 indicate increasing randomness; values less than 8 indicate increasing aggregation. Mean values of bait density and their standard errors were also calculated, the latter by the 'Bootstrap' resampling procedure (Efron 1981). These were expressed as 'weight/area' by multiplying absolute numbers of baits by the mean weight of baits. Areas of each block that were bait-free were estimated from the proportion of all transects combined (for lengths greater than 20 m) that had no bait.

Bait acceptance. The effectiveness of the different sowing strategies was assessed by capturing samples of possums and inspecting for Rhodamine B dye, which indicated bait consumption. All possums were captured by leg-hold traps over a period of 3 nights. Approximately 100 traps were positioned at 30- to 50-m intervals along 12 transects in each block. They were set against trees in recesses in the ground, covered with fine litter, and lured with rose-oil-flavoured flour.

Possums were killed and inspected at a central site. Body weight and weight of mesenteric fat (Bamford 1970) were measured to describe the mean condition of possum populations as described in section 2.5.2), as this was considered likely to influence bait acceptance (Bamford & Martin 1971). Where possums were not obviously marked with Rhodamine dye around the mouth and paws or in the gut, a UV light was used for closer inspection since dye marking wears away after a few days (Morgan 1981). The distance from each capture site to the nearest bait along a westward (i.e. across flight paths) 1-m-wide transect was recorded as an index of relative bait density in the vicinity of captured possums. Approximately 10% of possums were captured at sites where no bait was found within 100 m along the transect. An arbitrary value of 120 m was used for these possums since 100 m was nominally the largest gap expected (i.e. in block 2). Mean values of distances to baits from marked and unmarked possums in each block were compared by '*t*' tests.

3.3.2 Results

Uniformity of bait size. Compared to baits sampled during other possum control operations (Morgan unpubl. data) pellets were of uniform size, with 92.3% weighing 2-6 g and the mean weight being 4.3 g (SD = 1.3). The pilot did not report any binding of bait in the sowing bucket, and it was therefore assumed that any gaps in bait distribution were not a result of blockages in the bucket.

Bait dispersion, density, and bait-free areas. All bait dispersion data fitted the negative binomial distribution (although the probability of baits not being aggregated in block 1 approached significance) (Table 3.3). The degree of aggregation of baits can therefore be assessed using k values. Bait dispersion was clumped in all four blocks, with k values all well below 8. As expected, the highest degree of aggregation was in block 2, where gaps in sowing were deliberately created. In block 1, where flight paths were not marked, bait dispersion was more clumped than in blocks 3 and 4 where flight paths were marked.

Table 3.3 Degree of uniformity of bait dispersion based on goodness of fit (χ_2) to the negative binomial.

Block	Goodness of fit (χ^2)	Probability of difference from negative binomial distribution	k
1	10.30	0.07	1.24
2	1.42	0.71	0.97
3	4.34	0.23	1.40
4	2.52	0.96	1.85

In block 1, the recorded bait density was 25% less than the expected density (Table 3.4), and more than one-third of the block was estimated to be bait-free (Table 3.5). In block 2, where the flight paths were marked, bait density was close to that expected. Just over one-half of the block was bait-free, close to the expected value for the alternately sown swaths. Despite flight paths being marked in block 3, density of baits (sown at 3 kg/ha) was 25% higher than expected and one-quarter of the block was bait-free. In block 4, which was sown at the highest rate (10 kg/ha), the density of baits was close to the expected value and only 12% of the block was estimated to be bait-free.

Table 3.4 Actual bait density achieved under different nominal sowing rates.

Block	Nominal sowing rate (kg/ha)	Actual mean density (SE) (kg/ha)	% deviation from nominal rate
1	5	3.75 (0.35)	-25.0
2	5*	4.84 (0.60)*	-3.2*
3	3	3.76 (0.43)	+25.3
4	10	9.23 (0.67)	-7.7

* Figures given are for treated ground area only as alternate swaths were sown.

Table 3.5 Proportion of bait-free areas in each block, calculated from the length of bait-free sections (>20 m) on transects.

Block	Transect distance sampled (km)	No. bait-free sections	Mean length of bait-free sections (m) and SE	Estimated % of block bait-free
1	2.4	17	48.8 (12.3)	34.4
2	1.9	19	53.2 (11.5)	52.6
3	1.3	12	28.3 (4.3)	25.4
4	2.1	8	31.3 (4.7)	12.2

Bait acceptance. A sample of 503 possums was captured on the four blocks over 3 nights (successive nightly captures comprising 32.8, 31.0, and 36.2% of the total). From a total of 1146 trap-nights this gives an overall catch rate of 44%. Body condition of the population was poor. Nearly all possums were affected by extensive loss of fur in the thoracic and upper abdominal regions, and the mean weight of mesogastric fat was 6.7 g (SE = 0.5), which indicates a total body fat content of only 5.8% using the predictive equation given by Bamford (1970). Mean body weight was also low at 2.54 kg (SE = 0.04) compared with 3.18 kg (SE = 0.08) for a population sampled during the winter of 1979 in similar habitat at Kaiangaroa Forest 60 km to the north-east (Morgan 1982).

The patterns of bait acceptance over 3 nights in the four blocks were influenced by gaps in bait distribution, but not by the use of flight line marking or by sowing rate. In block 2, where large gaps in bait distribution were deliberately created, unmarked possums were caught on all three nights, unlike in other blocks (Table 3.6). A significantly higher percentage of possums was caught in gaps in bait distribution (no bait found up to 100 m west) in block 2 than in blocks 3 and 4 ($\chi^2 = 31.6$, d.f. = 1, $P < 0.001$; $\chi^2 = 25.9$, d.f. = 1, $P < 0.001$ respectively), which were also sown along marked lines (Table 3.7). Moreover, a significant percentage (56%) of the unmarked possums caught in block 2 were caught in gaps in bait distribution (Table 3.7) and mean distance to bait was significantly greater for unmarked possums (84.8 m) than for marked possums (44.4 m) ($t = 3.09$, d.f. = 138, $P < 0.001$; Table 3.8). This poorer bait availability resulted in a significantly higher proportion of unmarked possums being captured in block 2 (11.4%) than in block 3 (2.5%) ($\chi^2 = 7.8$, d.f. = 1, $P < 0.01$), despite baits being sown at a lower rate in block 3. Comparing the percentage of unmarked possums in blocks 2 and 4 (5.0%), the difference was significant only at the 90% level ($\chi^2 = 3.1$, d.f. = 1, $P < 0.1$).

Table 3.6 Numbers of marked and unmarked possums caught over 3 nights in the four blocks.

Block	Night	No. of possums caught		
		Total	No. unmarked	% unmarked
	1	6	6	
1	2	39	0	
	3	45	0	
	Total	130	6	4.6
	1	42	9	
2	2	39	5	
	3	59	2	
	Total	140	16	11.4
	1	44	2	
3	2	40	1	
	3	38	0	
	Total	122	3	2.5
	1	33	4	
4	2	38	1	
	3	30	0	
	Total	101	5	5.0

In block 1, where flight lines were not marked, a significantly higher proportion of possums were captured in gaps in bait distribution (no bait found up to 100 m west) than in blocks 3 or 4 ($\chi^2 = 4.37$, d.f. = 1, $P < 0.01$; $\chi^2 = 5.20$, d.f. = 1, $P < 0.05$, respectively). Nevertheless, all possums captured in block 1 after the first night had found and eaten bait (Table 3.6), and there was no difference in the percentage of unmarked possums (4.3%) compared with either blocks 3 (2.5%) or 4 (5.0%) ($\chi^2 = 0.85$, d.f. = 1, $P = 0.36$; $\chi^2 = 0.01$, d.f. = 1, $P = 0.91$, respectively) even though the sowing rate in the three blocks was different. In addition, unmarked possums caught in blocks 1, 3, and 4 were not significantly associated with gaps (Table 3.7).

In comparing the effects of different sowing rates, acceptance of bait in blocks 3 and 4 was similar, despite the three-fold difference in density of bait on the ground: after night 3 all possums captured had eaten bait (Table 3.6). Only two possums in each block were found in gaps in bait distribution (Table 3.7), and mean distances to baits averaged <10 m on both blocks (Table 3.8).

Table 3.7 Association between bait acceptance (i.e. number of possums marked and unmarked) and gaps in bait distribution (i.e. baits not present within 100 m west of captured possums).

Block	Bait distribution	No. of possums caught (%)		χ^2	P
		Marked	Unmarked		
1	Baited	112 (95)	6 (5)	0.64	0.42
	Gaps	12 (100)	0 (0)		
2.	Baited	96 (93)	7 (7)	8.26	<0.01
	Gaps	28 (76)	9 (24)		
3.	Baited	117 (98)	3 (2)	0.05	0.82
	Gaps	2 (100)	0 (0)		
4.	Baited	94 (95)	5 (5)	0.11	0.74
	Gaps	2 (100)	0 (0)		

Table 3.8 Proximity of captured possums to baits.

Block	Mean distance * (m) west to bait (and SE)			
	Marked possums		Unmarked possums	
1	17.1	(3.1)	4.2	(1.0)
2	44.4	(4.2)	84.8	(12.4)
3	9.4	(1.5)	8.3	(3.3)
4	8.4	(0.9)	4.2	(1.8)

* Value of 120 assumed where no baits found within 100 m west of capture site

3.3.3 Discussion

Bait-free areas as refuges in control operations. Although the poor bait distribution produced by the unguided sowing in block 1 did not increase the proportion of possums not finding baits, the deliberately created gaps in bait dispersion in block 2 did result in a significantly higher proportion of possums being caught in bait-free areas and a significantly higher proportion of captured animals being unmarked (relative to block 3). The unmarked possums give some indication of the proportion of the population likely to have survived if the baits had contained 1080 poison. On average, unmarked possums from block 2 had only to move 85 m in a westerly direction over 3 nights to find bait and less in the easterly direction as untreated swaths were only 100 m wide. This suggests that some possums may have very restricted movements over a period of 3 nights, and that they may, therefore, survive a poisoning operation by failing to locate bait even where there are relatively small gaps in bait distribution. Bigger gaps than those used in this trial occur regularly in routine control operations: in six operations the maximum gap between sown swaths varied from 170 to 350 m (Morgan 1988). Failure of possums to find bait was therefore more likely in these operations (in which the kill varied from 29.2% to 86.0%) than in this study.

Influence of population density and condition on bait acceptance. Except for the possums in block 2, where the slow rate of bait taking was attributed primarily to the gaps in bait distribution, all possums captured in the other blocks had eaten bait by the end of the 3-night period, confirming earlier acceptance trials in which 95-100% of possums ate bait (Morgan 1982). Population densities of possums in pine plantations generally range from about 0.44/ha up to 3/ha (Clout & Barlow 1982). The trap-catch rate of 44% at Waimihia was converted to a population density of more than 5/ha using a model based on calibrated trapping (Batcheler *et al.* 1967). This density is high for this type of habitat and would be expected to create strong competition for a limited food resource (which is consistent with the poor condition of the possums). However, high levels of bait acceptance (i.e. 95%) can be expected during winter even in populations of possums in good condition at low density (see section 2.2). Bamford & Martin (1971) suggested that population density and possum condition could be used to predict the success of aerial poisoning, but availability of food at the time of baiting may be a more direct influence (this is investigated in Chapter 4).

3.4 Use of navigation guidance systems to improve coverage

During the early 1980s, research was being undertaken to improve the efficiency of aerial application of fertiliser to plantation forests using a navigation guidance system ('Decca Flying Flagman') (Hedderwick & Will 1982). Aircraft were fitted with a radio transmitter, and radio signals were reflected back to an on-board receiver from two ground-based 'transponder' stations. By triangulation, an on-board computer was then able to determine the position of the aircraft, and through a simple system of calibrated LEDs, the pilot was able to navigate a flight-path calculated by the computer with accuracy of around ±10 m. Successive flight paths were calculated incrementally by the computer using a specified swath-width. Although the system had proved very effective over the typically flat terrain of many plantation forests, its use in the hilly country where possum control was usually undertaken was untested.

Towards the end of the 1980s the first systems using GPS (Global Positioning System) became available (Hurn 1989). These systems were similar to the Decca system, the main difference being that the navigation signals were received from satellites orbiting the earth. Initially, the number of satellites available was insufficient to ensure signal reception at all times, and a reference calendar was used to determine when the system could be used. Developed originally by the US military, it was made available for civilian use only with a varying degree of inaccuracy (i.e. up to 100 m) deliberately introduced to the signal. For aerial baiting, greater accuracy was required and this could only be corrected by referencing the signal received to that of fixed receiver stations within radio-contact of the aircraft-mounted system being used. This was termed differential GPS, or, DGPS. However, in 2000, the signal corruption was removed by the US military making available navigational guidance with accuracy of less than 10 m.

Data-logging by both systems enabled the production of appropriately scaled flight paths that could be overlaid on maps. Any gaps that were revealed could then be treated with baits by programming coordinates into the guidance system for re-location and treatment.

3.4.1 Assessment of the benefit of navigational guidance systems

Methods. I assessed the benefit of using navigational guidance systems in aerial control operations, by comparing data on coverage and kill (assessed as described in section 3.1.2) in operations conducted during 1991-93 with and without navigational guidance systems (Morgan 1994b). Six operations using navigational guidance systems were monitored by the Department of Conservation, but data on coverage were collected in only three of these. Flight-path maps were, however, inspected. Mean kills from these six operations were compared with kills presented in section 3.1.2 from seven operations in which navigational guidance systems were not used.

Results. No gaps in bait coverage were detected in the three operations using navigation guidance that were surveyed. In those that were not surveyed, coverage was assumed virtually complete because data-logging revealed regularly spaced flight paths with few gaps over 50 m being detected, and no bait blockages were reported in sowing equipment. The mean kill obtained in the six operations was 89.5%, significantly higher than the mean kill of 74.5% for the seven operations where navigation guidance was not used (t = 3.2, d.f. = 11, $P < 0.01$) (Table 3.9). High levels of kill (mean = 92%) were achieved in five of the operations, but one operation (Egmont) achieved a slightly lower kill of 78% for unknown reasons.

Conclusions. In practice the Decca system proved to be less reliable than later GPS systems. Both systems require constant signal reception, and since the Decca system used transponders located on the ground, it was not always possible to maintain 'line of sight' between the aircraft and transponders in hilly country. Not only did GPS ensure that signal reception was more assured, but an increase in the number of orbiting satellites to 24 by 1998 has ensured that reception is now available at any time, anywhere on earth. GPS has therefore become the standard for aerial navigational guidance.

Table 3.9 Bait coverage and possum kill in aerial control operations where navigation guidance systems was used. Data were compared with those in Table 3.1.

Location of operation (coordinates given in Appendix 1)	Navig. guidance system	Bait sowing rate (kg/ha)	% coverage	% kill
Titiraupanga, Bay of Plenty	GPS	10	Assumed 100	97
Rangitoto Range, Waikato	Decca	10	100	93
Moerangi, Waikato	Decca	10	Assumed 100	92
West Taupo, King Country	GPS	10	Assumed 100	89
Waipoua Forest, Northland	GPS	5	100	88
Mount Egmont, Taranaki	GPS	5	100	78

Use of navigational guidance systems showed that improved coverage and kills could be achieved giving greater relief from damage. A second benefit conferred by the improved control was the longer period of relief from damage, and therefore control expenditure. During the 1970s and 1980s, the average kill achieved in control operations was about 70% (Morgan *et al.* 1986). At an average rate of breeding (i.e. rate of increase = 1.4), and assuming no repopulation by immigration, recovery to 90% of the former population would take a minimum of 9 years. A kill of 95%, however, would increase the recovery time to a minimum of 16 years (Spurr 1981). For recovery to 50% of the former population, the period of relief increases from 3 to 9 years.

A third benefit of improved coverage was the potential for reducing the amount of bait used, which formed the focus of my subsequent research (section 3.5).

3.5 Minimum sowing rate required for effective control and trends in management

Aerial poisoning operations in the early 1970s typically applied baits at rates of 15-45 kg/ha (Batcheler 1978), with carrot baits generally applied at higher rates than pellet baits. As possums theoretically need to eat only one or two correctly prepared baits to receive a lethal dose of 1080, and possum population densities range from 0.3 to 25 possums/ha (Cowan 1990), it would appear that excessive amounts of 1080 bait were used in past control operations. Indeed, application rates often exceeded the biomass of possums being targeted. Because of problems with many small, sublethal baits (Batcheler 1982), and large gaps in coverage, excessive amounts of bait were applied so that possums would eventually find and eat a lethal bait. These problems were largely solved by improved standards of bait preparation and the introduction of navigational guidance systems. In the late 1980s, I initiated field trials to determine if sowing rates could be substantially reduced without lowering operational effectiveness.

3.5.1 Methods

Field trials. In addition to the field trial at Waimihia described above (section 3.3), five further field trials were conducted in conjunction with possum control agencies to assess the general effectiveness of lower bait application rates in a variety of habitat types (Morgan *et al.* 1997). Effectiveness was determined by either the percentage of possums eating non-toxic baits or the percentage killed using 1080-treated baits. All trials were carried out in winter or early spring. Baits were applied using a helicopter with an underslung bucket in each trial. The buckets were calibrated to deliver the desired rates by changing the size of the aperture at the base of the bucket to regulate the flow of baits on to the spinning distributor disc. Bait output from the bucket, operating on the ground with the distributor disc stationary, was established at different aperture settings. A known weight of pellets was placed in the bucket and the time for this material to be delivered through the aperture to the disc was recorded by stopwatch. Aperture settings were then selected that gave the desired nominal application rate using the formula given above (section 3.3.1). Complete coverage of target areas was obtained using helium balloons to mark flight paths in the earliest trial, and navigational guidance systems (Decca Flying Flagman or GPS-based systems) in all other trials.

Non-toxic pellet baits were used in the first three trials. These were surface-treated with 0.1% w/w Rhodamine B dye (ICI Ltd) as a bait marker (Morgan 1981). Baits were applied at rates ranging from 1.5 to 10 kg/ha (Table 3.10) over blocks of approximately 100 ha. The first trial has been fully described above (section 3.3). The second and third trials were carried out in mature mixed kauri-hardwood forest at Waipoua and Puketi forests, Northland, where understorey vegetation was typically very dense, thus concealing some baits. Gaps were again created in these trials. At Waipoua, a central portion of the one-square-kilometre block (i.e. 100 ha) measuring approximately 300 x 1000 m (i.e. 30 ha) was left untreated, and data were compared for the entire block and the part that was treated. At Puketi, alternate 100-m swaths were left untreated in one block. After baits had been available to possums for one night, a sample of at least 40 possums was collected from each treatment block by use of cyanide paste (Animal Control Products) and leg-hold traps 2-5 days after bait was applied. The percentage of possums eating baits in each block was determined from rhodamine-dye-marking of the mouth, forepaws, and digestive tract (Morgan 1982).

Toxic baits were used in a further three trials. Pellet baits (No. 7) containing 0.15% wt/wt 1080 (confirmed by laboratory assay) were applied (Table 3.10). Two trials were conducted in relatively 'open' pine plantations at Puketiro and Whakatikei, west of Upper Hutt, while a further trial was conducted in more densely vegetated native podocarp-hardwood forest near Otaki. Larger blocks of between 140 and 300 ha were selected for these trials as the effectiveness of the application rates was assessed by the 'trap-catch' method (Warburton 1996). Twenty leg-hold traps were set at 20-m intervals along 10 randomly located lines before and after poisoning. After poisoning, the lines were relocated parallel to and at least 200 m away from pre-poisoning lines to ensure that an independent estimate of the population surviving poisoning was obtained. The mean population reduction was obtained from the reduction obtained from individual pairs of lines.

Trends in sowing rates used by management. Data were obtained from regional councils, the Department of Conservation, and several summary reports (Batcheler 1978; Spurr 1993a; Anon. 1994; Brown & Aruchelvam 1995) on application rates and costs for 141 operations between 1973 and 1997. Mean application rates for operations using pellet (n = 90) and carrot (n = 51) baits were calculated for successive five-year periods and costs of control per hectare were adjusted to 1997 values using the Consumer Price Index (CPI). Costs included direct operating costs but not overheads. The relationships between costs and sowing rates were examined by regression analysis.

3.5.2 Results

Field trials. Reducing the application rate of baits did not result in poorer effectiveness except where coverage was incomplete (Table 3.10).

Table 3.10 Effectiveness of different application rates of pellet baits determined from percentage of possums eating non-toxic baits or percentage of possums killed by toxic baits.

Trial site/forest type (coordinates given in Appendix 1)	Date	Bait type	Application rate (kg/ha)						
			10	5	5 (with gaps)	3.7	3	2	1.5
Waimihia/pine	June 1985	Non-toxic	95	95	76		98		
Waipoua/indigenous	May 1990	Non-toxic		97	87				
Puketi/indigenous	May 1992	Non-toxic		83	71		84		92
Puketiro/pine	July 1995	Toxic		83		93		95	
Whakatikei/pine	June 1996	Toxic		97		100		95	
Otaki/indigenous	Oct 1996	Toxic				73		87	
MEAN % (SE)			95.0 (-)	91.0 (3.2)	78.0 (4.7)	88.7 (8.1)	91.0 (7.0)	92.3 (2.7)	92.0 (-)

All application rates gave a mean effectiveness within the range 88.7-95.0%. There was no trend of declining effectiveness when the rate was reduced. In the three trials where gaps were created, mean effectiveness was 78.0%, which was significantly less than the mean effectiveness of 91.7% in equivalent, completely covered blocks (t = 5.0, P = 0.04, d.f. = 2).

Trends in sowing rates used by management. Application rates of baits declined markedly between the mid-1970s and the late 1990s (Fig 3.3). Typically, pellets are now applied at only a quarter of the rate used in the mid-1970s, while the application rate of carrot has also been more than halved. This has provided appreciable cost-savings, particularly for pellet operations as this type of bait comprises a higher proportion of the total cost than carrot bait. At current rates of 5 and 10 kg/ha for pellet and carrot baits respectively, savings of around \$50/ha and \$30/ha are being made when compared with application rates of 20 years ago. Although my database is incomplete, it shows that in 1994 pellet and carrot baits were each applied over at least 100 000 and 130 000 ha respectively. This represents a saving of \$8.9

million in the cost of aerial control for that year compared with the average cost in the mid-1970s.

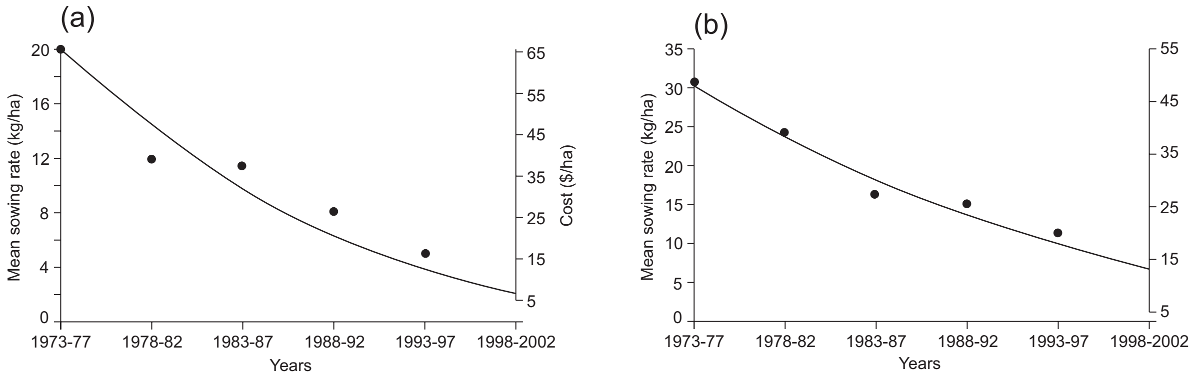


Fig 3.3 Mean application rates (with trend-line fitted by eye) for a) pellet and b) carrot baits from 1973 to 2002. CPI-adjusted cost for these control operations was highly linearly related to application rate (cost for pellets=3.34(rate)-1.14, r^2=0.93, $p<0.011$; cost for carrot=1.61(rate)+0.81, r^2=0.89, $p<0.005$), so the corresponding cost for each application rate is indicated by the right hand axis. Points on the graphs refer to sowing rate.

3.5.3 Discussion

Aerial application rates of possum baits have declined markedly over the last 25 years providing substantial cost-savings that can be used to extend the area over which possum populations are controlled. This has occurred in part because improvements in bait quality and application technology have increased the chances of possums finding a lethal quantity of bait, and perhaps in part due to the involvement of possum control agencies in the trials described here. At the present conventional application rate for pellets of 5 kg/ha, approximately 900 lethal baits/ha are being delivered to populations that number only 0.5-25 possums /ha (Cowan 1990). It is therefore not surprising that the trials indicate that further reductions, to 2 kg/ha or even lower, should be effective even in forest types where thick understorey vegetation may conceal many baits. A further $3 million, at least, could be saved annually if rates were lowered to 2 kg/ha, assuming that 150 000 ha is aerially treated annually with each bait type. However, in some habitats high numbers of other vertebrate pests that may eat baits, such as rodents, deer, and pigs, may make further reductions more risky. The effectiveness of low application rates in such habitats should therefore be assessed. In the future it should be possible to accurately distribute (using GPS) 'quality assured' baits with a selected field-life at rates as low as 0.5 kg/ha (i.e. 100 baits/ha). If this proves to be effective, not only will further substantial cost-savings be gained, but the reduced exposure of baits to living and non-living parts of the ecosystem will further enhance the environmental safety ofaerial 1080 operations.

3.6 Contemporary review of the findings of aerial sowing studies

3.6.1 Use of navigational guidance systems

The field trials conducted between 1985 and 1995 demonstrated, both empirically (by monitoring actual operations) and experimentally (by simulating operations in the field), the need for aerial operators to take advantage of newly developing navigational guidance systems. Monitoring bait distribution after routine operations (section 3.2) showed major gaps in dispersion, and kill was found to be highly dependent on coverage. The controlled field trials (section 3.3) showed that inaccurate flying, though not serious enough to affect the extent or rate of acceptance of bait by possums, could cause considerable error even over a small, easily navigable area. Even relatively small gaps (compared with what had been recorded after operations) of 100-m width was sufficient in trials to lead to possums surviving. Thus a major reason for reduced operational effectiveness had been clearly identified and a solution was needed.

Hedderwick & Will (1982) had shown that the 'Decca Flying Flagman' electronic guidance system improved the aerial application of fertiliser granules over New Zealand pine plantations. Reductions in the application rate more than offset the cost of using the system. The system proved to be unreliable, however, in both my own research trials and the few control operations on which it was used, due to the loss of the necessary 'line-of-sight' signal transmission in hilly country. A breakthrough was made, however, when the first GPS-based guidance systems became available in the early 1990s. Software, initially developed by Trimble Navigation (Christchurch), was first used by Richmond Harding of Wanganui Aeroworks in carrying out fertiliser topdressing over pine plantations in Northland in 1991. He was able to demonstrate complete coverage (though not necessarily application of bait) of the target area by overlaying flight-path printouts over maps. Other aerial operators were quick to see the advantage of the system and by the end of the decade all aerial possum control operations were required by management agencies to involve the use of GPS-based systems. While it is difficult to separate out the effect of GPS-use alone on operational effectiveness, a study conducted by Brown & Arulchelvam (1995) found that it was the only factor among 20 investigated that had a measurable effect on operational kill rates. The power of their analysis was probably insufficient to detect the significance of other factors, as it has been shown more recently that prefeeding, for example, significantly increased the average kill in aerial 1080 carrot baiting operations (Henderson & Frampton 1999).

The next step in the development of GPS-guided bait application is the linkage of bait application information to flight-path data. Such a system, 'Smartflow', is under development (P. Bradley, Lakeland Helicopters, 20 June 2002, pers. comm.) and comprises a bait-flow sensor linked to continuous video-recording of bait flow and GPS data on aircraft position. Should an interruption to bait flow occur, this is logged on GPS output and can be checked against the video recording before programming new flight paths to treat any areas that are verified as untreated. I believe it will be desirable to further develop such sytems to ensure uniform coverage at a constant sowing rate. This could be achieved by incorporating terrain mapping data (i.e. gradient changes) in the programming of flightpaths, and linking the required variation in sowing rate to the regulation of bait output as a helicopter aircraft traverses the flightpaths. Since windspeed also affects flying speed, a further correction to bait output could be achieved through linkage to the GPS-programming.

3.6.2 Reducing sowing rates

The finding that bait distribution could be reduced, with no loss of rate of acceptance, from 10 kg/ha to 3 kg/ha in pine plantations (section 3.3) with an open understorey on flat terrain had important management implications. Reducing sowing rate of pellets from the commonly used rate of 10 kg/ha to 3 kg/ha would reduce operational costs by about 65%. While density of pellets on the ground differed, the dispersion pattern was similar under both sowing rates, and despite aggregation of baits, sufficient were dispersed for possums to find them. This is because at 3 kg/ha over 500 baits (of mean weight 6 g) were provided per hectare, and possums on average eat only two to three 1080 pellet baits before feeding stops (Morgan 1990a). Although many baits are concealed in thickly vegetated forest habitat, it is possible that many of these are still located by possums. Studies on possums' response to various 'lures' showed that baits attract possums over a distance of up to 1.5 m (Morgan *et al.* 1995). While this is clearly inadequate to attract possums living in gaps to find baits, it may be great enough to ensure that they are detected by nearby possums. These findings led to the later trials (section 3.5), which confirmed that sowing rates could be reduced to as little as 2 kg/ha with no loss of effectiveness. Pest managers have continued to reduce the amount of bait being applied since this work was published such that a typical operation now involves application of non-toxic prefeed at 2 kg/ha followed by toxic baits at 2 kg/ha (Animal Control Products 2003). The cost-savings that have been achieved have made a major contribution to the feasibility of recently introduced strategies for sustaining control of possum populations (see Chapter 8).

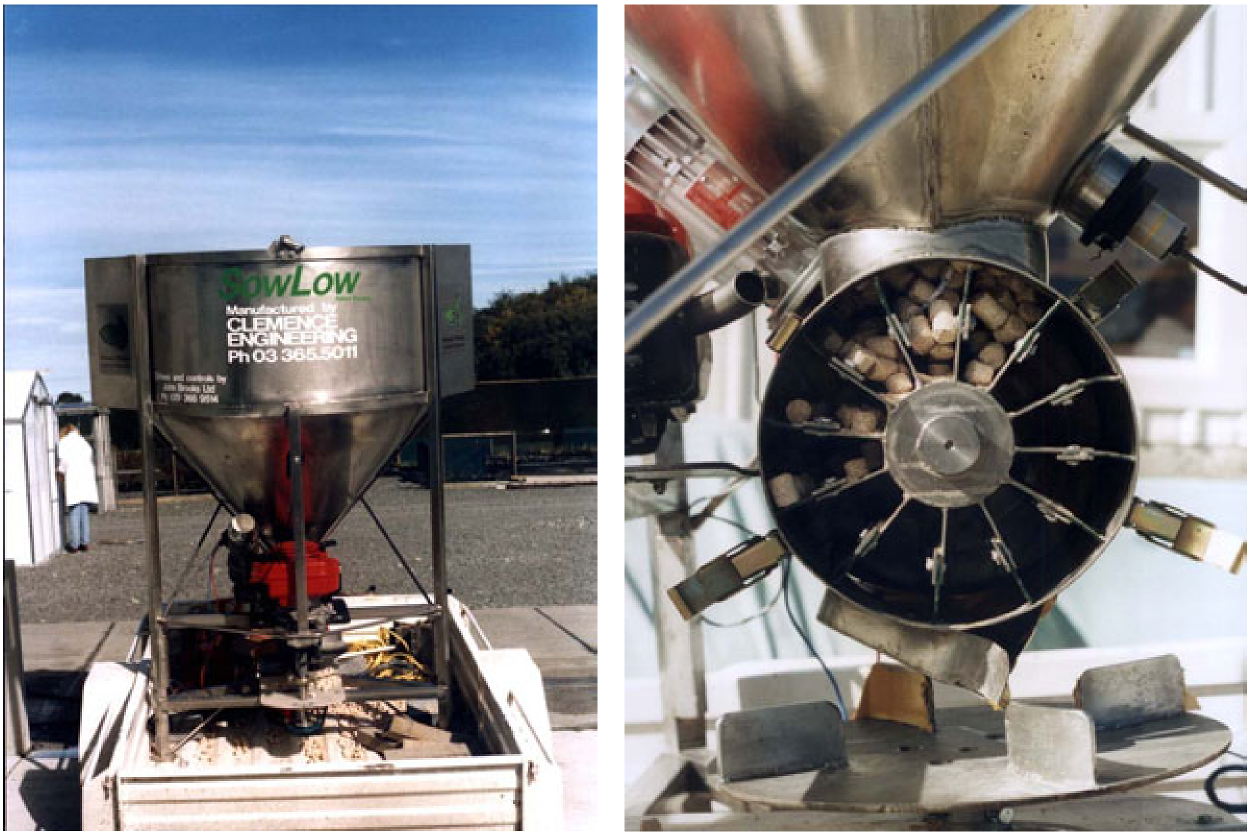
3.6.3 Environmental safety

A reduction in the amount of 1080 bait being distributed during control operations would be expected to reduce the hazards to non-target species and reduce environmental contamination. However, no formal research has yet been undertaken in the field to assess possible environmental benefits of lower sowing rates. One reason for this is that aerial 1080 operations as a whole generally have little environmental impact when conducted under high standards (as described in Chapter 7). A substantial body of research data has been collected leading to the conclusion that operations typically have no impact on populations of common birds and invertebrates (see review by Spurr 2000). Other extensive research has shown that, following aerial 1080-baiting operations, there is minimal contamination of watercourses or wildlife, and no risk to humans through food chain contamination (see review by Morgan & Eason 2003). Nevertheless, individual birds and other animals have been found killed after aerial 1080 operations (Spurr 2000), and a few (<5%) of the 1465 water samples collected in control zones after 26 aerial-1080 baiting operations contained trace concentrations of 1080 (all well below the WHO recommended permissible maximum) (Eason 2002). While the environmental risks of aerial 1080 operations are considerably lower than has been suggested by many critics (section 8.1.3), avoidance of any individual non-target mortalities and any contamination of water samples is desirable. Lowering the sowing rate of baits is expected to help further reduce the risk of such incidents occurring.

Environmental safety is also being enhanced by the recent development of computer-based tools for planning, monitoring and documenting aerial control operations. GIS-based mapping of target areas can now be used to describe the boundaries of target areas to a much higher degree of accuracy than previous, hand-drawn boundaries (Woodhouse 2002). This also enables more accurate calculation of bait requirements and more rapid recalculation of target areas and flightpaths should the need for revisions occur (e.g. a change to the boundaries of the target area). Since the coordinates of boundaries and sensitive sites within target zones (e.g. watercourses) can be digitised and incorporated in aircraft flightpaths, I believe further development should link these data to the control of sowing buckets to automatically prevent bait being applied in areas where it is not intended.

3.6.4 Development of improved sowing machinery

In the Waimihia field trial (section 3.3), bait was distributed very inaccurately even when flight paths were marked. Since bait of relatively uniform and optimal size was used, and an even flow was maintained during sowing, it is probable that either the pilot did not strictly adhere to the flight paths, or, alternatively, the sowing bucket used did not spread bait evenly within a swath. Furthermore, the machinery used in the trial proved difficult to calibrate accurately, particularly at the lowest sowing rate (3 kg/ha) from which bait density on the ground deviated by 25%. Most helicopter underslung buckets and topdressing aircraft used in possum control until the mid-1990s were designed primarily for distributing fertiliser or seed at much higher rates, and relied on the principle of baits being gravity-fed through an aperture of variable size. This inevitably leads to blockages in flow when the aperture is reduced to a critical size, usually somewhere around rates of 3-4 kg/ha. Sowing equipment that can deliver bait accurately and evenly over a wide swath at rates as low as 1 kg/ha (equivalent to approximately 160 baits of mean weight 6 g) was needed to maximise the cost-effectiveness of large-scale possum control. This resulted in the later development of purpose-designed machinery (reviewed by Spurr 2002), including a new type of helicopter-borne sowing bucket developed collaboratively by myself, M. Thomas (formerly of Landcare Research), Clemence Engineering (Christchurch), John Brooks Electrical Engineers (Christchurch), and Amuri Helicopters (North Canterbury). The 'SowLow' bucket (NZ Patent No. 299454) (Fig. 3.4a) produced utilises a variable-speed motor, which can be controlled by the pilot, to regulate the revolution speed of a metering device (Fig. 3.4 b), and hence the delivery rate of baits to a constantly revolving spinner plate. The device is now in operational use, and given the recent interest in the use of lower sowing rates as a result of this research, it is expected that it will become commercially available.



(a) **(b)**

Fig 3.4 (a) The 'SowLow' aerial-bait delivery bucket and (b) the bait-delivery mechanism comprising a 'paddle wheel' chamber that is controlled by a variable-speed motor (diagonally mounted at left-rear).

Chapter 4. Bait Acceptance in Relation to Seasonal Changes in Food Availability

4.1 Introduction

In this chapter, I describe new research in which I examined the influence of seasonal foods and possums' body condition on their acceptance of bait. Until the early 1990s, aerial control of possums had been conducted mostly in winter, when the condition of male possums is poor and that of female possums is declining (Bamford 1970). At this time, the foods favoured by possums, particularly fruits and new foliage, are thought to be in shortest supply and it would therefore seem likely that possums are most likely to accept artificial foods in winter. In addition, in winter, disruptions to patterns of livestock management caused by the sowing of toxic bait over forest adjacent to farmland is minimised, carrots (the traditional and cheapest bait) are most readily available, and, in some regions, the weather is most settled.

During the 1990s, an increasing number of aerial control operations were conducted (particularly by the Animal Health Board for Tb control), and this placed a greater demand on the services of possum managers and their staff, on the manufacturers of alternative cereal baits, and on aerial operators. Furthermore, aerial control had been considered inappropriate in winter in some regions due to the likelihood of extended periods of rainfall at that time of the year (e.g. Northland). These factors encouraged possum managers to spread the increased workload outside the traditional winter baiting season (Kelton 1995).

My earlier trials on bait acceptance, with limited seasonal factoring, suggested that aerial control operations may be less successful in summer. At Kaingaroa Forest (a pine plantation), acceptance was inadequate (68%) in summer, and contrasted with high acceptance (95%) in the same area during winter (see section 2.5.3). A study was therefore conducted during 1996-2000 to provide data from a representative range of forest types (in which possum control is sometimes warranted) to assess whether aerial control outside of the traditional season is generally likely to be effective.

4.2 Methods

4.2.1 Site selection and timing of trials

Three areas were selected that broadly represented much of the forest habitat over which the Department of Conservation conducts aerial control of possums. No possum control had been conducted in the areas for at least 2 years, thus avoiding the possible confounding effect of bait shyness on bait acceptance assessments. The Herekino Forest, Northland, was selected as a mixed hardwood-broadleaf forest with rich plant diversity, no history of ungulates, and a recently established (i.e. colonised around 1960; Pracy 1974) possum population. The Moki Forest in inland Taranaki represented a tawa-kamahi forest of average plant diversity, with a well-established ungulate and possum population (possums established around 1920; Pracy 1974). The Cobb Valley in Nelson is vegetated with low-diversity beech forest, in which ungulates are common and the possum population has been long-established (since around 1900; Pracy 1974) but remains at low density.

In each area, 100-ha sites were selected for a series of eight bait acceptance trials. These were conducted in each season (i.e. summer (January), autumn (April), winter (July), and spring (October)), and repeated in a second year to provide for greater statistical rigour. The Herekino and Moki trials were conducted from October 1996 to July 1998. The Cobb trials were conducted from July 1997 to April 1999, to stagger the cost and complexity of establishing trials.

4.2.2 Treatments

Bait preparation. Non-toxic, cinnamon-flavoured No. 7 cereal-based pellet baits (Animal Control Products, Wanganui) were used in all trials. The baits were treated with 0.1% wt:wt Rhodamine-B dye as a marker to indicate the percentage of possum populations eating bait in each trial (Morgan 1981, 1982). A solution of dye was prepared by mixing 60 mL of 'Been there' (a spray marker product containing 40% rhodamine - FIL Industries) with 1.44 L of water, and 1.5 L of the solution was slowly added to 25 kg of pellet baits (i.e. one bag) in a concrete mixer and gently mixed until all baits were evenly coated. Baits were then spread on a sheet of plastic for several hours until dry and then rebagged. Baits were dyed within 1 month of manufacture and were used no longer than 2 months after dyeing.

Bait quality. The effects of dyeing and subsequent drying on bait palatability were assessed in a series of trials using captive possums. Pellets were tested before dyeing, while damp following dyeing, and after storage at room temperature for 1, 4, 30, and 60 days following dyeing / drying. In each trial, 100 g of No. 7 pellets and 100 g of fresh (i.e. <2 months old) RS5 pellets (Animal Control Products, Wanganui) were presented to 20 individually housed possums for 16 h overnight. Palatability was estimated from each possum's consumption of No. 7 pellets expressed as a percentage of the combined consumption of No. 7 and RS5 pellets, and mean values and standard errors calculated.

4.2.3 Bait distribution

Baits were distributed by helicopters fitted with sowing buckets calibrated to sow baits at a rate of 5 kg/ha, the average rate used for aerial control of possums when the study started in 1996 (Morgan *et al.* 1997). Pilots used GPS guidance systems to minimise the likelihood of gaps occurring in baiting coverage. Each trial was conducted in a previously unbaited 100-ha block of forest. In the Herekino and Moki forest trials, blocks were surrounded by forest, but in the Cobb Valley trials, blocks were located on alpine valley slopes with lower boundaries along the forest edge at the valley bottom.

4.2.4 Assessment of bait acceptance

After allowing possums one night to feed on baits, a sample of up to 60 possums were trapped using Victor No. 12 leg-hold traps lured with a mixture of flour and icing sugar treated with approximately 0.1% wt:wt orange oil (Bush Boake Allen, Auckland). Traps were placed only at locations where several baits were visible, and were set for up to 4 nights. The trapped possums were killed humanely by one or two firm blows to the back of the head and removed to a central necropsy site. The marked proportion of the population eating at least one bait was assessed by inspecting the paws, mouths, and stomach contents (Morgan 1981). Those that were not clearly marked were inspected under ultraviolet light for the presence of the orange fluorescence characteristic of Rhodamine B. Possums showing minor traces of Rhodamine B dye were not regarded as bait acceptors as it is likely they had either only nibbled bait (i.e. eaten only the equivalent of a sublethal quantity) or had been inadvertently marked by standing on baits. At the same time, stomachs were collected from all possums in each sample and frozen for later determination of favoured foods, 'indicating' those that might be predictors of poor bait acceptance.

The acceptance of bait by possums in each trial was expressed as the proportion of trapped possums showing clear dye-marking, and 95% binomial confidence intervals were applied to this proportion. Differences in bait acceptance between trials, between areas, years, and seasons were tested using logistic regression. Models were fitted using maximum likelihood, and tested for effects using likelihood ratio tests (Collett 1991). To test the hypothesis that some possums may survive in the canopy through failing to encounter bait, attempts were made to sample possums from the canopy at night by spotlight-shooting. As only a few possums were collected from only five of the trials, they were combined into a single sample for comparison with the combined sample of ground-dwelling possums captured. A chi-square test (with Yates' correction for small sample sizes) was used to compare the proportions of marked animals in the two samples.

4.2.5 Possum condition

The condition of possums in each 'seasonal trial' was assessed using two indicators of the total amount of stored body fats (Bamford 1970). Firstly, the fat surrounding the stomach (mesenteric fat) was removed and measured, and differences in the mean weight of mesenteric fat compared by analysis of variance (ANOVA). Differences in mean mesenteric-fat weights between year and season (within each area) were tested using ANOVA with 'year' and 'season' as fixed effects. Fat weights were square-root transformed to satisfy assumptions of ANOVA. *Post hoc* Bonferroni pairwise comparisons were used to identify where differences existed. Secondly, as described in section 2.5.2, the body weight and length of each possum were measured and the regression of ln (weight) on ln(length) generated a slope. Confidence intervals for the slope values were obtained using the formula given in Zar (2002, p. 337). The slope is an index of the mean growth characteristics of a population (Taylor 1979) and can be used as an index of population condition (Overton *et al.* 2003, Prasaad 2001). Analysis of covariance was used to determine if the slopes of the weight-to-length relationships varied between year and season. Where there was an overall difference between years and seasons, *t*-tests were used to make further comparisons. These two measures of condition were then separately regressed against bait acceptance to determine if body condition influenced possums' response to bait. To normalise data for analysis, the proportion of animals accepting baits was arcsin-square-root transformed and mesenteric fat was square-root transformed.

4.2.6 Food availability and usage by possums

At the same time as each field baiting trial was conducted, the availability of natural foods preferred by possums was assessed in the treatment block. A list (see Appendix 2) was compiled of 10-12 forest plants occurring commonly in each area and whose foliage, flowers, or fruits had been identified in the literature as preferred by possums (e.g. Fitzgerald & Wardle 1979; Coleman *et al.* 1985). The occurrence of such preferred species was assessed during the initial selection of sites.

The phenology of these favoured possum-food plants in six classes (abundance of new leaves, flower buds, flowers, green fruit, ripe fruit, and fruit on the ground) was assessed on at least 30 plots of 5-m radius located at 20-m intervals (40-m at Cobb Valley) on transects within each block. For each species, the nearest scorable specimen to the plot centre was selected. To boost sample sizes of uncommon selected species, additional specimens were scored off plots as encountered along the transects. Phenology descriptions were adapted from methods described by Payton *et al.* (1997), and were assessed subjectively using a 5-point scale of abundance (0-4). High phenology scores (3 or 4) were rare, particularly for flowers and fruits, so for analysis, phenology descriptions were reduced to two classes: ‘absent or rare’ (scores 0 and 1), and ‘common’ (scores 2, 3, or 4). The percentage of trees (combining all species monitored) with ‘common’ phenology scores was calculated for the six classes of plant food (i.e. new leaves, buds, and flowers, and for green, ripe, and fallen fruit).

Data were used as indices of the abundance of possum food resources seasonally in each area, and regression analysis was carried out to determine if bait acceptance (arcsin-square-root transformed) was influenced by broad availability. Four ‘indices’ were used, combining data for individual species, i.e. (1) all phenological classes (i.e. 2-4), (2) new leaves, (3) flowers and buds combined, (4) ripe fruit in trees and on the ground combined.

The percentage of trees with possum browse, assessed on a 5-point scale (Payton *et al.*, 1997) was calculated for common species (at least 15 specimens on and off plots) scored in each of the four seasons (both years combined). The data were graphed, and tested for seasonal differences using chi-square (4x2) contingency tables for those species that were frequently browsed (at least 20% browsed in at least one season). There were insufficient data to test for seasonal differences for less common or less frequently browsed species. The abundance of fresh possum faecal pellets beneath the trees used for browse assessment was scored on a 4-point scale (0-3).

I acknowledge the substantial contribution made in the design and implementation of these botanical aspects of the study by colleagues, Dr J. Coleman and Mr P. Sweetapple.

4.3 Results

4.3.1 Bait quality

After dyeing with Rhodamine-B solution, drying and storage of the pellets resulted in palatability changes typical of No. 7 pellet baits (see Henderson & Frampton 1999). Trials with captive possums indicated that there was a short-lived increase in palatability after pellets were dampened during dyeing, but after drying and over the next 60 days, there was a slow but consistent reduction in palatability (Table 4.1). However, even after these 60 days, palatability was still above the 40% threshold suggested as the minimum recommended specification for effective possum baits (Henderson & Frampton 1999). Baits used in the trials can therefore be considered to have been representative of baits routinely used in possum control operations.

Table 4.1 Palatability of No. 7 pellets tested against fresh RS5 pellets as a control using 20 caged possums in each trial. All No. 7 pellets were approximately 1 month old before dyeing.

Trial no.	Treatments of No. 7 pellets	Mean palatability (%)	SE
1	Undyed	44.2	7.1
2	Dyed and still damp	73.1	7.7
3	Dyed, dried and stored for 1 day	48.6	8.7
4	Dyed, dried and stored for 4 days	46.9	8.1
5	Dyed, dried and stored for 7 days	44.6	7.7
6	Dyed, dried and stored for 30 days	44.6	6.1
7	Dyed, dried and stored for 60 days	40.2	7.9

4.3.2 Bait acceptance and possum condition

High levels (i.e. 85-100%) of bait acceptance were recorded for trapped possums in all of the 24 trials conducted, with acceptance less than 90% in only three trials. The number of possums caught in trials varied from 31 to 72, and altogether 1163 possums were caught. Differences in bait acceptance between seasons varied with area (χ^2_3 = 22.91, P < 0.001).

This is not surprising as the areas were selected to provide a broad representative range of the different forest types in which aerial control of possums is undertaken by the Department of Conservation. The three areas were therefore treated separately for further analysis. Results are summarised in Figures 4.1-4.3. Significant differences are indicated where confidence intervals do not overlap other central values.

Herekino Forest. Bait acceptance was consistently very high in Herekino Forest in samples varying from 30 to 71, and totalling 372 possums. At least 90% of possums were clearly marked on all sampling occasions and 100% on half the occasions (Fig. 4.1a). There was no evidence of a significant difference in bait acceptance between seasons ($\chi^2_3 = 7.43$, $P = 0.060$) or between years ($\chi^2_1 = 0.90$, $P = 0.343$, interaction effect: $\chi^2_3 = 1.42$, $P = 0.699$). Possum condition as indicated by mesenteric fat showed an annual cyclical pattern (Fig. 4.1b) varying significantly between seasons ($F_{3,327} = 28.89$, $P < 0.001$) and between years ($F_{1,327} = 24.53$, $P < 0.001$). The annual pattern was similar between the two years ($F_{3,327} = 2.35$, $P = 0.072$), with possums carrying significantly more fat in autumn of the second year. Lowest fat weights were recorded in spring of both years and the first summer. Comparisons of the slopes of body weight to length (Fig. 4.1c) showed that this index of condition remained constant throughout the year. Although significant overall variation was detected between the length to weight regression slopes ($F_{7,355} = 10.50$, $P < 0.001$), subsequent comparison of slopes found no difference between any individual pairs of slopes ($P > 0.05$). In examining the relationship between bait acceptance and condition, there was a significant positive correlation with length to weight slope ($F_{1,6} = 117.9$, $P < 0.001$) which explained 95.2% of the variation in the proportion of possums that ate bait. However, there was no relationship between acceptance and mesenteric fat weight ($F_{1,6} = 1.00$, $P = 0.356$).

Moki Forest. In Moki Forest, 95-100% of all possums ate baits except in spring and winter of the first year (Fig. 4.2a). Quarterly catches of possums varied from 31 to 65, and totalled 336. Overall, there were significant differences between seasons ($\chi^2_3 = 24.49$, $P < 0.001$), due to the significantly lower acceptance in spring and winter of the first year compared with all other sampling occasions. Acceptance overall was higher in the second year ($\chi^2_1 = 4.66$, $P = 0.031$). The pattern in seasonal variation was, however, consistent between years ($\chi^2_3 = 7.17$, $P = 0.067$). The mean weight of mesenteric fat varied jointly with both season and year ($F_{3,444} = 13.61$, $P < 0.001$) (Fig. 4.2b). Possums had significantly more stomach fat only in autumn and winter in the first year. Analysis of covariance showed that the length to weight slopes varied between the eight sampling occasions ($F_{7,355} = 16.95$, $P < 0.001$), though with no similarity in pattern between years (Fig. 4.2c). There was no correlation between bait acceptance and either mesenteric fat ($F_{1,6} = 0.183$, $P = 0.684$) or length to weight slope ($F_{1,6} = 0.756$, $P = 0.418$).

Cobb Valley. Bait acceptance in the Cobb Valley was consistently high, exceeding 93% in all but the second spring trial when 87.5% of possums ate bait (Fig. 4.3a). Quarterly catches of possums varied from 40 to 72, and totalled 455. There was no significant difference in bait acceptance between years ($\chi^2_1 = 0.07$, $P = 0.791$) or seasons ($\chi^2_3 = 5.40$, $P = 0.145$), and no interaction effect ($\chi^2_3 = 3.02$, $P = 0.389$). Mesenteric fat weights varied throughout the sampling period, differing significantly in seasonal pattern between years ($F_{3,359} = 7.52$, $P < 0.001$) (Fig. 4.3b). Mean weights were highest in autumn but this increase was significant only in the second year. Analysis of covariance showed that length to weight slopes varied between the eight sampling occasions ($F_{7,355} = 8.335$, $P < 0.001$) (Fig. 4.3c), but with no similarity in pattern between years. There was a significant positive correlation between bait acceptance and the mean weight of mesenteric fat ($F_{1,6} = 26.74$, $P = 0.002$) that explained 81.7% of the variation in the percentage of animals that ate bait. There was no relationship, however, between bait acceptance and the length to weight slopes ($F_{1,6} = 0.388$, $P = 0.556$).

(a)
(b)
(c)

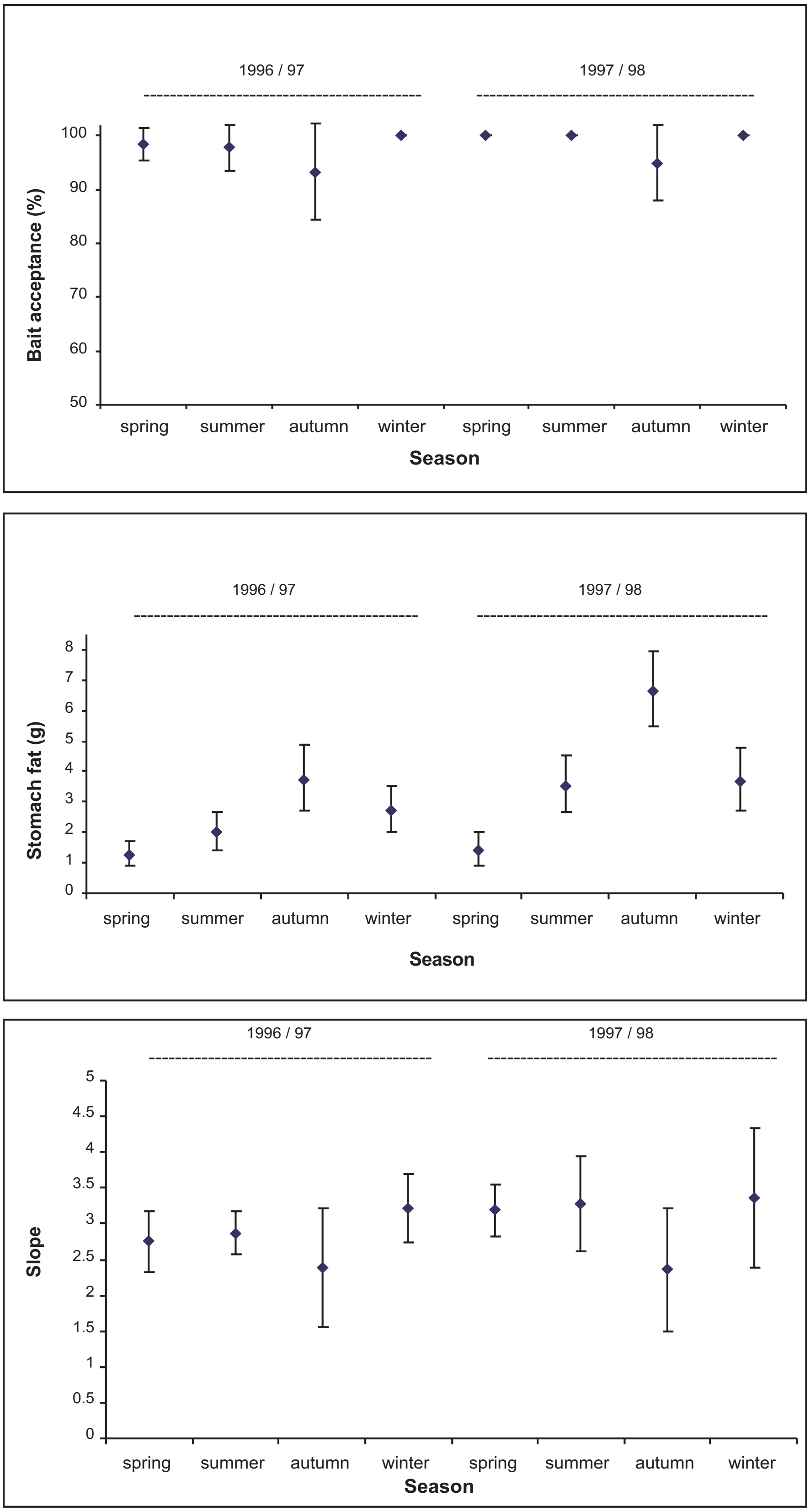


Fig. 4.1 (a) Percentages of possums accepting bait, (b) mean weights of possums' mesenteric stomach fat, and (c) slopes of the regression of possum body length and weight at Herekino Forest in each season over two successive years. Vertical bars are 95% confidence intervals.

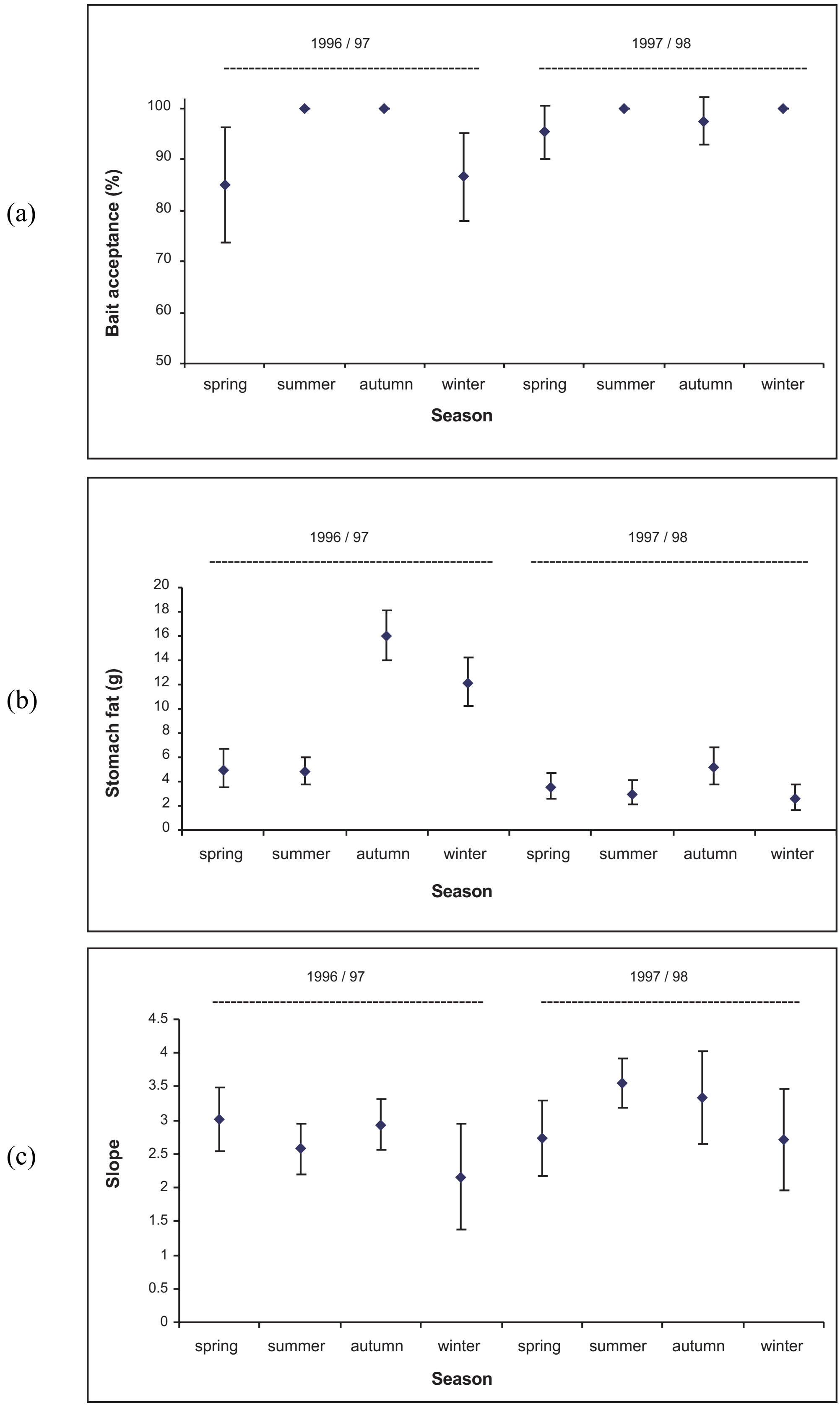


Fig. 4.2 (a) Percentages of possums accepting bait, (b) mean weights of possums' mesenteric stomach fat, and (c) slopes of the regression of possum body length and weight at Moki Forest in each season over two successive years. Vertical bars are 95% confidence intervals.

(a)

(b)

(c)

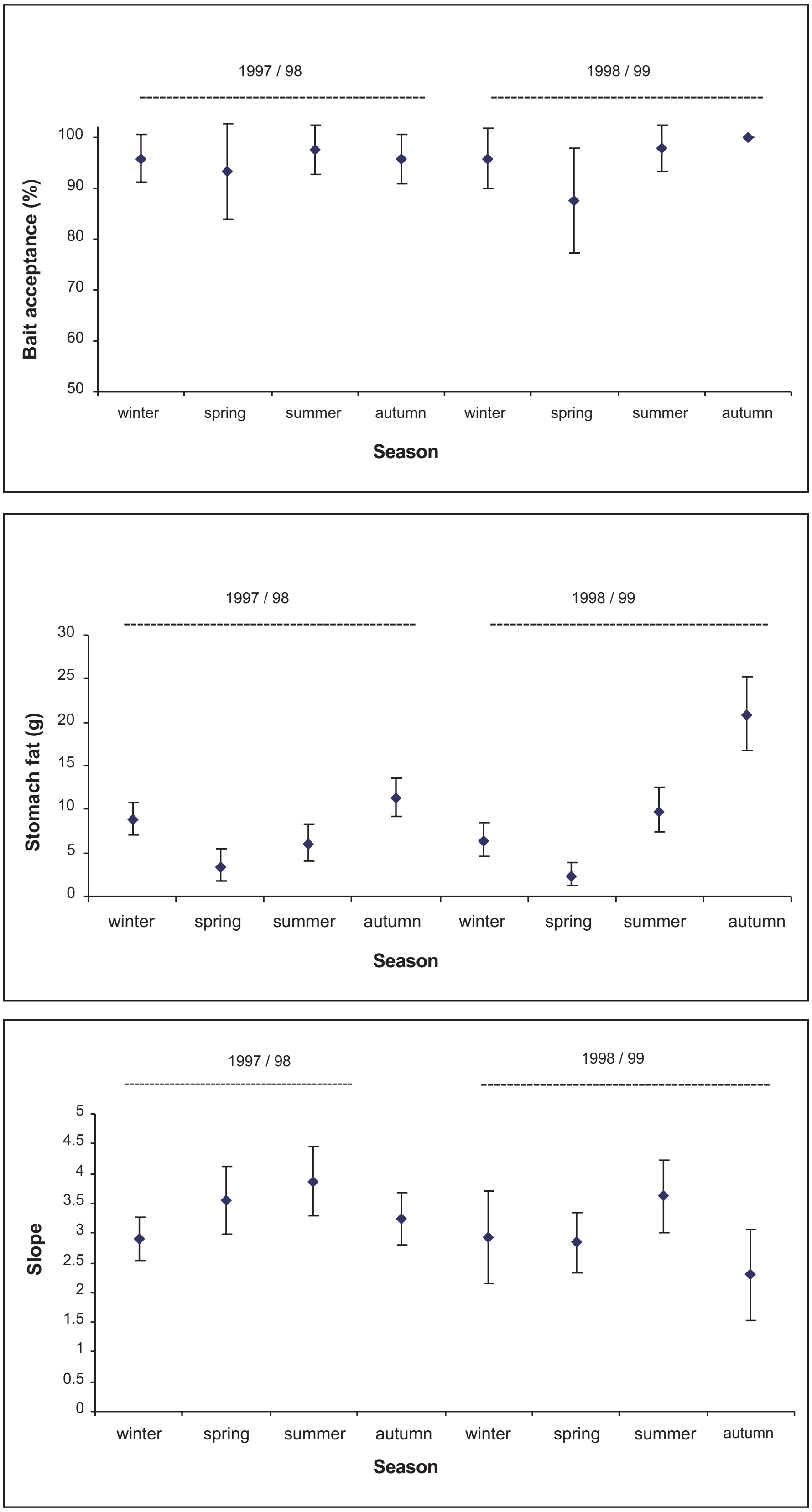


Fig. 4. 3 (a) Percentages of possums accepting bait, (b) mean weights of possums' mesenteric stomach fat, and (c) slopes of the regression of possum body length and weight in the Cobb Valley in each season over two successive years. Vertical bars are 95% confidence intervals.

4.3.3 Bait acceptance by canopy dwelling possums

A combined total of 33 possums were collected from the canopy in trials at Herekino and Moki forests. Of these, 9 (27.3%) were unmarked and this percentage was significantly different to the percentage unmarked (12.0%) of possums sampled (n = 341) at ground level in all trials ($\chi^2_1 = 4.8$, $P = 0.029$).

4.3.4 Bait acceptance in relation to food availability

The plant species monitored in each area together with their scientific names are listed in Appendix 2. They included forest emergents such as taraire, rewarewa, rata, and tawa; canopy species such as towai, kamahi and hinau; subcanopy species; lianes (bush lawyer), and forest herbs. The range, frequency, and identity of trees and shrubs palatable to possums varied sharply between study sites. Herekino Forest was botanically the most diverse, and because of its recent colonisation by possums, species palatable to possums were abundant. Moki Forest best represented a 'typical' hardwood-softwood forest modified by the presence of possums over a prolonged period. The Cobb Valley Forest typified the low diversity normally encountered in beech forests but did contain some rare species that are vulnerable to possum browsing (e.g. *Pittosporum patulum*).

The phenology of possum-favoured plants showed, as expected, marked seasonal patterns (Figs 4.4-4.6). The production of new leaves in particular followed very strong and predictable patterns at all sites (i.e. strong peaks in spring and summer). However, bait acceptance at each site (as shown in Figs 4.1-4.3) was found to be independent of the abundance of combined favoured plant foods as assessed using the four indices developed. Correlation coefficients indicated that fitted regressions accounted for only <1-22% of the variation in proportions of possums eating bait, and none of the regressions approached significance (Table 4.2).

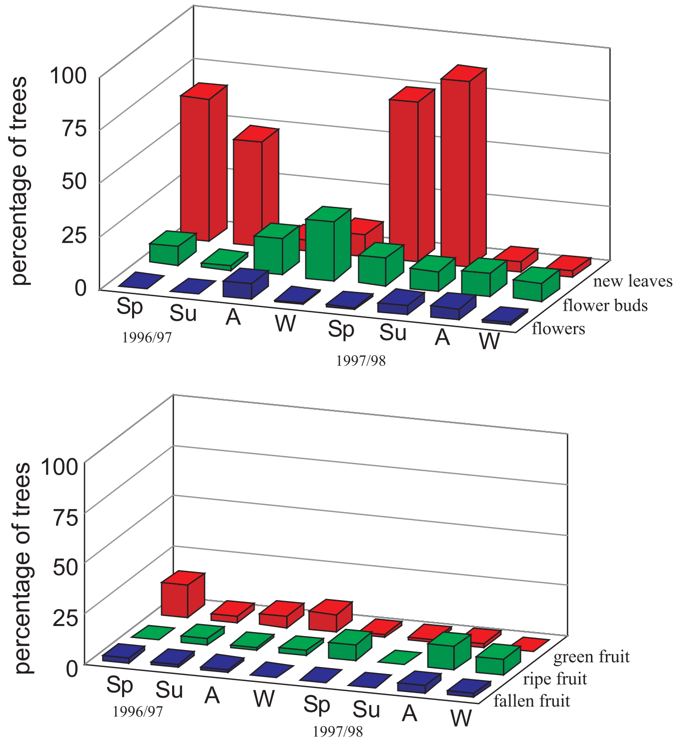


Fig. 4.4 Mean phenology index for (a) new leaves, flower buds, and flowers, and (b) fruit of plant species favoured by possums at Herekino Forest in each season over two successive years.

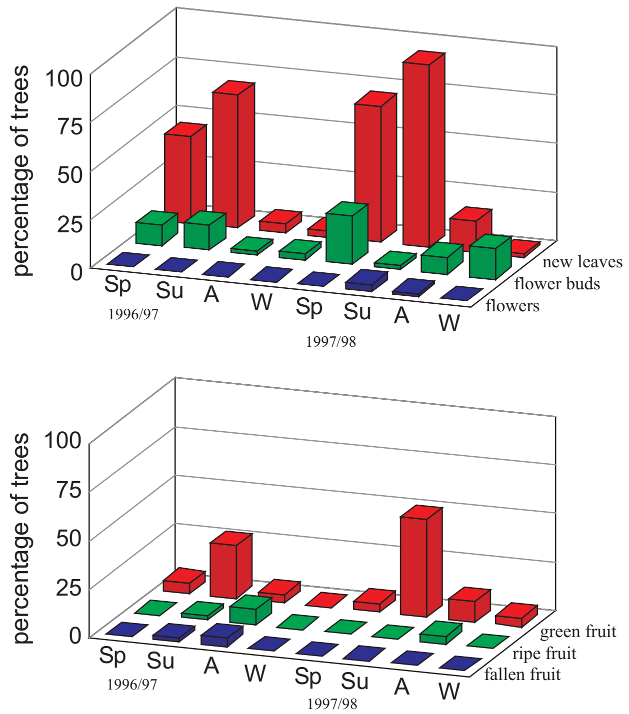


Fig. 4.5 Mean phenology index for (a) new leaves, flower buds, and flowers, and (b) fruit of plant species favoured by possums at Moki Forest in each season over two successive years.

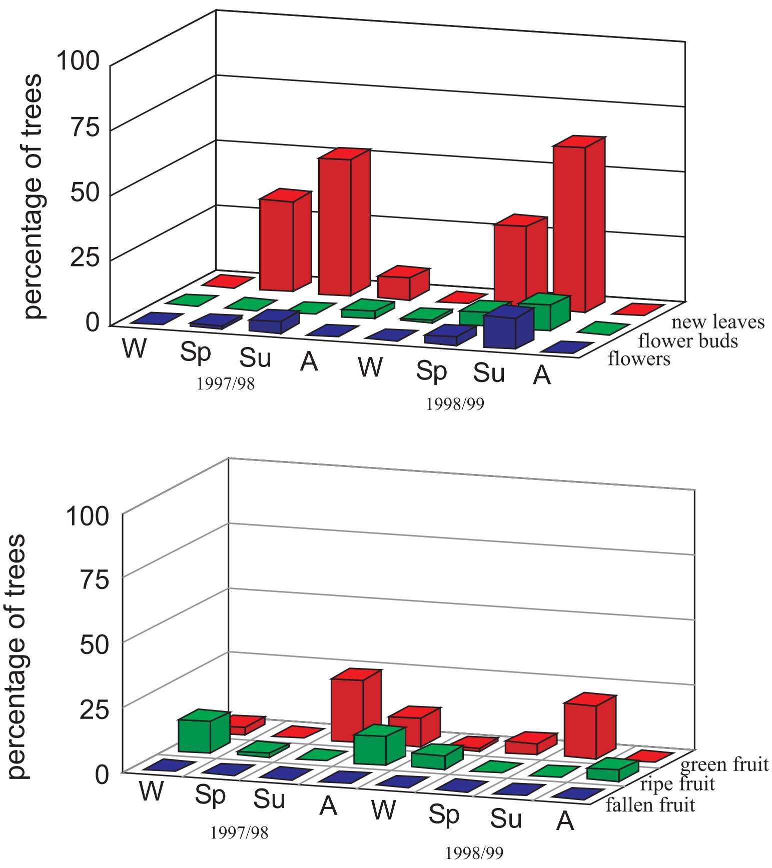


Fig. 4.6 Mean phenology index for (a) new leaves, flower buds, and flowers, and (b) fruit of plant species favoured by possums in forest, Cobb Valley, in each season over two successive years.

Table 4.2 Summary of regression analyses of possums bait acceptance on food abundance (expressed as four indices). Statistics given are the correlation coefficient (r^2), F value, and probability (P) of significant regression.

Site	Index of food abundance	r^2	F (d.f. = 1,6)	P
Herekino Forest	All plant foods	0.14	0.97	0.36
	New leaves	0.22	1.68	0.24
	Flowers and buds	0.12	0.82	0.40
	All ripe fruit	0.02	0.10	0.76
Moki Forest	All plant foods	0.09	0.06	0.47
	New leaves	0.02	0.11	0.75
	Flowers and buds	<0.01	0.01	0.91
	All ripe fruit	0.17	1.18	0.32
Cobb Valley	All plant foods	0.01	0.04	0.86
	New leaves	0.04	0.23	0.65
	Flowers and buds	<0.01	0.04	0.85
	All ripe fruit	0.04	0.25	0.63

4.3.5 Possum 'sign' (browse, faecal pellets)

Herekino Forest. The level of possum browse observed varied seasonally on two of the three frequently browsed common species monitored in Herekino Forest. Browse on kohekohe was highest in summer (χ^2_3 = 10.7, P = 0.13), while browse on towai was highest in summer and winter (χ^2_3 = 47, P < 0.001). Browse on five-finger did not vary seasonally (χ^2_3 = 4.2, P – 0.24), with high levels recorded in all seasons.

Moki Forest. Three common species were frequently browsed by possums present at Moki Forest: kamahi, mahoe, and tawa. Levels of browse on all three varied seasonally (χ^2_3 = 18-34, P < 0.002), with high levels of browse recorded in spring and summer on tawa and in spring, summer, and autumn on both kamahi and mahoe.

Cobb Valley. Only two possum-preferred plant species, bush lawyer and lancewood, were common within the study blocks in all four seasons in the Cobb Valley. Possum browse on bush lawyer varied seasonally from a high of 47% of plants in winter to a low of 4% of plants in autumn (χ^2_3 = 15.7, P = 0.001). Although the percentage of lancewood trees browsed by possums varied from 52% in winter to 0% in summer and autumn, there were insufficient data to perform a contingency table test.

Few recognisable possum faecal pellets were recorded on the plots in any season at Cobb Valley, and during some surveys in both Herekino and Moki forests. This paucity of faecal pellets was due to low possum densities at Cobb Valley, and at Herekino and Moki forests heavy rain immediately prior to some surveys apparently destroyed or washed away most faecal pellets.

4.4 Conclusions

4.4.1 Seasonal bait acceptance

The most important findings from this two-year study were that, in three different forest types, (1) possum populations showed very high levels of bait acceptance in all seasons, and (2) this was not influenced by seasonal variation in combined, favoured food plants. I would therefore expect that had toxic baits been used (instead of non-toxic baits), equally high acceptance of bait would have been achieved, assuming that baits were adequately toxic and masked to conceal the 1080 (Chapter 5). Before further discussing the study findings (and 'temperature' as a possible seasonal influence), the likelihood of experimental error should be considered.

4.4.2 Possible experimental error

Bait acceptance trials are based on the fact that possums remain marked for about 7 days after consuming at least one rhodamine-dyed bait (section 2.4). However, this dye technique does not permit estimation of the amount of bait eaten by each possum. It is possible that some marked animals may have eaten less than the equivalent of a lethal quantity of bait (i.e. one 6-g bait). Inspection of stomach contents showed that almost all possums captured had extensive dye marking or fluorescence in the stomach. Only in 40 of 1160 possums inspected (i.e. 3.4%) was I unsure if marking represented consumption of at least one 6-g bait (i.e. representing a lethal amount for most possums). These possums were classified as non-acceptors so as to not overestimate acceptance. Despite this caution, some possums may still have been wrongly interpreted as having eaten at least one bait, leading to some overestimation of acceptance. Equally I may have falsely rejected a few possums and marginally underestimated acceptance. On balance, I believe the two possibilities tend to negate each other, thus reducing the overall error in estimated acceptance.

That such errors in interpretation are likely to have been minor is supported by the finding that little variation occurred in bait acceptance in this study; in other, both earlier (section 2.5) and recent (Coleman *et al.* 1999) bait acceptance trials, greater differences in acceptance were found. Thus the technique is clearly capable of revealing lower levels of bait acceptance, where they exist. I therefore conclude that in the present study, high proportions of possums ate bait in all seasons at all three sites.

Small variations in palatability of different batches of bait used in different trials may have occurred due to natural variability in the grain ingredient. However in seven trials testing the consistency and stability of a synthetic (and therefore strictly controllable) gel bait, RS5 pellets were used as the reference (control) material (Morgan *unpublished data*). Since values of 52-57% palatability were obtained, it appears that variations in pellet bait palatability are less than 5%, even disregarding any other sources of variation. Furthermore, the appreciable variability in bait palatability found in field trials (Fig. 2.1) was not reflected by similar differences in bait acceptance (Table 2.6).

While the data indicate high levels of bait acceptance in forest habitats in any season, some caution is expressed against this expectation. In a recent, similar study, bait acceptance was assessed among possums inhabiting a typical Westland farm/forest interface in the Waitaha Valley. Nine trials were conducted during late spring to early autumn over two consecutive years and found again that, while there was no strong evidence that baiting outside of winter would lead to operational failures, bait acceptance was consistently lower (mean 84%; range 73.1-91.4%) than in the present study (Coleman *et al.* 1999). The availability of highly favoured pasture species during the warmer months was considered to be a likely cause of the lower level of bait acceptance among possums living on the forest edge. This result reinforces the conclusion from my earlier bait acceptance trials (section 2.5) in relation to the summer trial in an exotic forest in which bait acceptance was significantly poorer than in all others. Possums were in very good condition and abundant highly favoured exotic grasses and herbs were noted in the plantation. In the present study, possums in the Cobb Valley were sampled from the forested slopes adjoining tussock grassland in the valley floor. That no seasonal effects on acceptance were noted, however, would suggest that possums were less inclined to feed on native grasses and herbs of mixed origin in the Cobb Valley.

4.4.3 The influence of condition and food availability on operational success

Possum condition and food availability were measured as the most likely seasonal variables to affect bait acceptance, other than adverse weather. Since bait acceptance remained high throughout the study in all three areas, and showed no consistency between areas in the little variability recorded, statistical assessment of the influence of these parameters on bait acceptance was compromised. However, the study has revealed some useful information on the applicability of the methods used, and alternatives that deserve further consideration.

Condition. The length-to-weight condition index was correlated with bait acceptance only at Herekino Forest, while a correlation with the mesenteric fat condition was found only in the Cobb Valley. While these relationships suggest the indices could be useful for localised prediction of bait acceptance, neither index proved suitable for general application, as also found by Coleman *et al.* (1999). The general unsuitability of the two condition indices as predictors of bait acceptance may reflect not only the lack of variation in bait acceptance data, but also the relatively good condition of possums in this study. For example, the length-to-weight slopes recorded earlier in five populations (Table 2.8) varied between 1.73 and 3.09, while the range in the present study was 2.2 to 3.7. Thus, in the present study, possum condition at each of the three sites remained high and relatively stable, compounding the difficulty of revealing a relationship with bait acceptance data of low variability. Where possum condition is more variable, predictive localised relationships with kill are possible, as demonstrated by Bamford & Martin (1971) who favoured the use of a length-to-weight relationships for this purpose (because it could be assessed quickly on live animals). Predictions of bait acceptance using these indices are, however, likely to be partly confounded by the deposition of fat that occurs before breeding to prepare females for lactation (Bamford 1970) and males for periods of food shortage when engaged in mating behaviour (Day *et al.* 2000). If these indices are to be used comparatively as predictors of bait acceptance or kill, comparisons between seasons in a particular area should be made, recognising the confounding effect of breeding-related changes in fat. The mesenteric fat index is likely to be more sensitive to recent seasonal environmental effects (mainly food abundance and climate) than length-to-weight slopes, which additionally represent the effects of animals' genetic origin and long-term environmental influences. With regard to practicalities, Bamford (1970) found that reliable prediction of total body fat was given by the mesenteric fat index rather than the and index based on length-to-weight ratios when sample size was small, but the latter index could be gained from live animals. However, as suggested in section 2.5.4, fat-based indices may lag behind changing food availability, and changes in the weight of the thymus gland (Ozoga & Verme 1978) may be a more useful measure of environmental stresses and predictor of bait acceptance.

Food availability. The lack of correlation between food indices and bait acceptance strongly suggests that fluctuation in the availability of the major components of possums' diet has little impact on bait acceptance. The study was designed to assess the influence of diet at such a broad level. Because bait acceptance did not vary significantly, it was not possible to use possums' stomach contents to identify 'indicator' foods associated with poor bait acceptance. Nevertheless, it is possible that some specific, sharply seasonally foods may influence possums' acceptance of baits over relatively short periods. Many New Zealand forest species exhibit mast fruiting, where large fruit crops are produced at irregular intervals (often every few years), e.g. hinau (*Elaeocarpus dentatus*) (Cowan & Waddington 1990) and beech (*Nothofagus*) species (Wardle 1984). Relatively little fruit, especially ripe fruit, was produced during the study, and no mast events occurred in any species measured. Masting of preferred fruit can cause dramatic changes in possum diet. For example, bush lawyer (*Rubus cissoides*) (foliage and fruit) comprised just 2% of possum diet at Waihaha, near Lake Taupo, in 1991-92, but during a heavy mast in March 1996, bush lawyer fruit comprised 80% of total diet, and more than 95% in 47% of stomachs (P. Sweetapple, unpublished data). If a mast event had occurred during the present study, the bait acceptance results may have differed. However, mast events may be rare where possum densities are moderate or high, as possum browsing on foliage, flowers, and green fruit of fruiting species may suppress them. For example, the heavy fruiting of bush lawyer at Waihaha occurred immediately after possum control, and hinau fruiting was shown to be suppressed by possum browse in the Orongorongo Valley, Wellington (Cowan & Waddington 1990). It is therefore particularly important that bait acceptance trials are conducted if fruit-masting of possum-preferred species is observed before scheduled control operations are conducted, as the present study was unable to test the influence of an abundance of specific, highly favoured foods on likely control success.

4.4.4 Influence of temperature on operational success

While this study used acceptance of non-toxic bait as a measure of likely poisoning success, empirical data gathered by Henderson *et al.* (1999b) for both Department of Conservation and regional council control operations showed that effectiveness of toxic bait varied seasonally. Combining aerial and ground-based operations, seasonal kills were ranked winter (86.1%, n = 28)>summer (82.3%, n = 32)>spring (81.5%, n = 12)>autumn (74.3%, n = 14). ($F_{3,39} = 3.67$, $P = 0.02$). As these operations were not conducted as replicated trials, some of the seasonal variation in the data may be attributable to other factors such as the type of bait used, toxic loadings, baiting coverage, climatic variables, or habitat differences. However, Veltman & Pinder (2001) collected data from 48 possum control operations between 1994 and 1999 to assess the influence of a number of operational variables on operational success. Mortality was not influenced by sowing rate, size of treated area, month, or year of the operation. Ambient temperature (at 2000 hours) was, however, found to influence population reduction, with those operations achieving kills of at least 90% occurring on nights colder than 9°C (at 2000 hours). Since 1080 disrupts the production of energy (see section 1.2.5), the findings are consistent with higher energy demand at lower temperatures rather than a temperature effect on feeding behaviour (i.e. bait acceptance). For practical purposes, the authors suggested restricting operations to the cooler months is the simplest way of countering this effect. However, it may be necessary to conduct some control operations in other seasons due to high winter rainfall, or excessive winter demand for baits, aircraft, and pest-control staff. In such cases, it may be possible to utilise ground-based methods of control such as presentation of 1080 baits in bait stations or as bait-piles, ensuring that all possums encountering baits are likely to consume a lethal quantity. Alternatively, the concentration of 1080 in baits required for effective control in warmer parts of New Zealand should be established as a basis for a new registration of 1080 use. Concentrations of 1080-masking flavours can be increased beyond current specifications with no effect on bait palatability (Henderson & Frampton 1999), but masking effectiveness at such higher concentrations needs evaluation.

In retrospect, it would have been useful to monitor temperature during the 24 seasonal bait acceptance trials to test whether the influence of temperature identified by Veltman & Pinder (2001) is mediated through bait acceptance, or, susceptibility to toxin. Between the three sites, the small seasonal differences in bait acceptance recorded were found to vary between areas. Assuming broad differences in temperature seasonally, the lack of a consistent overall seasonal trend in bait acceptance therefore suggests there was no relationship between temperature and bait acceptance. However, the LD_{50} to 1080 in possums at 23.5ºC was found to be significantly greater (by two and a half times) than that at 10.5ºC in cage trials (Oliver & King 1983) and I therefore conclude that Veltman & Pinder's observed effect of temperature on operational success is due to its effect on susceptibility to 1080 rather than an effect on bait acceptance.

4.4.5 Bait acceptance by canopy-dwelling possums

Although only a small sample of possums was collected from the canopy during bait acceptance trials, the higher proportion of unmarked animals compared with those sampled at ground level strongly suggests that some possums may survive aerial baiting through failure to encounter bait. It is possible, however, that this result overestimated the problem if baits remained palatable (and toxic in actual control operations) longer than the few days over which sampling was done, and canopy-dwellers then visited the ground, encountering baits. Nevertheless, the pellet baits used have a short field-life as indicated by the palatability assessments of dampened baits, and therefore the result is likely to be applicable to areas where the forest floor is likely to be damp. Such survival may represent one of the main reasons why some possums presently are able to survive aerial 1080 operations. It is therefore important that further data are obtained to strengthen the comparison, and if the result is confirmed, techniques must be devised for either distributing baits in the canopy, or attracting possums to ground level.

4.4.6 By-kill of rodent populations

Since the study began, an additional reason for conducting aerial control outside of the 'traditional' winter season has become apparent. While possums are usually the main target of such operations, high by-kills of rodents and mustelids can normally be expected (and are desired). Rodents are killed by primary poisoning (i.e. by eating the bait; Innes *et al.* 1995), and mustelids by secondary poisoning (i.e. when scavenging contaminated carcases; Alterio 1996; Murphy *et al.* 1999). Therefore, where protection of native birds is intended by aerial control of possums, and also rodents and mustelids, maximum benefit can usually be obtained if control is carried out in spring before chicks hatch. This strategy provides relief from predation during the critical first two months of many birds' lives, when they are confined to the nest before fledging. The need for such critically timed control (i.e. in spring) reinforces the need, in warmer parts of New Zealand, for 1080 baits containing a higher 1080 concentration. This may need to be considerably higher given the effect of temperature on LD_{50} values described above (section 4.4.4) and warrants further investigation in relation not only to lethality towards possums, but also to the consequent need for higher concentrations of 1080-masks (discussed in Chapter 5) and risks to non-target species.

Chapter 5. Non-learned Aversion Towards 1080 in Baits

5.1 Introduction

This chapter summarises and reviews past research I conducted during 1979-85 to further examine the possibility that some possums are innately averse towards 1080, as suggested by the 1979 Wainihinihi field trial described previously (section 2.5).

Several forms of *'behavioural resistance'* towards baits used in control have been identified in possums. In my field bait acceptance trials, up to 20% of naive possums were found to have refused non-toxic bait (section 2.5.3). Since these baits contained no 1080, this type of bait refusal is attributed to possums having an *innately low preference for the bait* relative to other naturally occurring foods (e.g. poor bait acceptance coincided with a natural food abundance in the summer Kaingaroa bait acceptance trial - Table 2.6). Where other pest species have been subjected to repeated control, this has selected survivors with *an innate wariness of new objects*. If such behaviour, termed *neophobia* (Cowan 1977), were genetically based, this may partly explain poor and declining rabbit kills in 1080 operations in Australia (Rowley 1958; Oliver *et al*. 1982) and in Central Otago (Fraser 1985). (Physiological resistance to 1080 in repeatedly poisoned rabbit populations is another contributory factor which is believed to reflect genetic selection (Twigg *et al*. 2002)). Similarly, it is possible that some possums surviving initial 1080 poisoning operations may be neophobic rather than just having low preference for baits. If so, repeated poisoning is likely to select for survival of neophobic possums resulting in declining control effectiveness. However, their slower breeding rate and longer generation time compared with rabbits would be expected to result in slower development of a proportion of populations that are neophobic (Hickling 1995).

While these two forms of behavioural resistance (i.e. low preference for bait and neophobia) threaten control effectiveness, they can, however, be overcome. Henderson & Frampton (1999) demonstrated an inverse correlation between bait palatability and sublethal poisoning, reinforcing the need to use baits of high palatability to ensure that all possums are potentially targeted. (The major influences on bait palatability are mainly controllable, as described in Chapter 7). They also showed that prefeeding should mitigate almost all neophobia: after 3 days of prefeeding the proportion of possums consuming less than 3 g of cereal pellet bait in the first 60 min of feeding (equivalent to the approximate maximum time possums feed on toxic pellets before toxicosis inhibits feeding – see section 5.2.2) declined from around 30% to 0%. This information has led to the development of 'best practice' advice to pest managers (e.g. Henderson *et al.* 1999b).

Two other forms of behavioural resistance that threaten control effectiveness are *innate aversion* and *learned aversion* (see Chapter 6) towards toxic baits. The Wainihinihi bait acceptance trial (section 2.5) showed that, while >95% possums generally accept non-toxic bait (except perhaps in summer when food availability is high), 32% and 17% of possums survived when 1080 poison was added to carrot baits at 0.1% and 0.2% wt/wt respectively and it was concluded that *innate aversion* (i.e. a non-learned, instinctive aversion) to the smell and/or the taste of 1080 was the reason. The poison has been described as odourless and virtually tasteless in its pure form (Atzert 1971), although it has a faint smell of vinegar caused by acetic acid impurity in its commercial form. A study was therefore conducted to determine more precisely the extent of innate aversion in captive possums to 1080 baits. The behavioural mechanisms adopted by possums in their first encounters with new foods, and the function of these mechanisms in bait aversion, were examined in pen trials. Flavours were tested for possum preferences, and the masking effectiveness of selected flavours in overcoming innate aversion to 1080 was assessed.

5.2 Pen trials to assess innate aversion

The study has been published in detail (Morgan 1990a). An abbreviated form of the paper is presented here, concentrating on the aspects of the study that led to improvement in the aerial control of possums.

5.2.1 Method

Bait types. Two bait types were evaluated, carrot and No. 7 cereal pellet baits (Animal Control Products, Wanganui). Carrot bait was prepared by chopping fresh carrots into chunks of approximately 6 g, and applying 0.15% 1080 and 0.1% Lissamine green dye to the surface of the baits, as is done for aerial baiting operations. Pellet baits also contained these additives as bait ingredients.

Observations of possums' responses to baits. Possums captured in parts of Canterbury, Westland, and Rotorua regions with no history of 1080 use were acclimatised to captivity for a minimum period of 6 weeks. They were then placed individually in one of three smaller (6 x 7 m) observation pens for a minimum of 4 days before observation of their response to the bait treatments. The husbandry used is detailed in New Zealand Forest Service (1982). The possums' behaviour was observed under controlled variable overhead illumination from a hut built into each pen. A 60-watt spotlight was also used, but a few animals that were sensitive to the lighting were viewed through a 'Zenascope' light-intensification device. Just before each observation period 12 baits of the same type were laid out. Each bait was mounted on a horizontally looped piece of 12-gauge wire about 25 cm above the ground to minimise interference from any smells on the ground. The baits were spaced 1-4 m apart in three rows of four, giving a distribution of approximately one bait per 2 m^2.

Observations started about 15 min before sunset as possums usually emerged 10 min either side of sunset. When the animal emerged, a stopwatch was used to time the behavioural response to baits (type of activity and number of baits investigated). The time lapse until each successive bait was investigated and the duration of each response were recorded. A standardised recording sheet was used. The responses were:

- Sniff
- Bite
- Reject the bait after sniffing (i.e. smell rejection)
- Reject the bait after biting (i.e. taste rejection)
- Eat less than 50% of entire bait
- Eat more than 50%, but not the entire bait
- Eat the entire bait in one visit.

When toxic baits were presented, notes were made every 15 min after bait was first eaten, and in between if unusual behaviour was observed. When possums showed little further interest in the baits, observations were stopped and an estimate was made of the percentage eaten of each bait. This was repeated the following morning in case baits were eaten after observations had stopped.

Flavour preferences. Preferences amongst a wide range of food flavours were evaluated for captive possums by adding flavour to barley, a staple food of which they never tired, and comparing the consumption of treated and non-treated barley. A different group of possums was used for this part of the study to avoid the possibility of learned responses to flavours confounding responses of 'naive' possums to baits. The 39 flavours, all concentrated fluids, were applied to the barley at the manufacturer's (Firmenich, Geneva) recommended concentrations (mostly 0.01% vol:wt).

Flavours were presented in groups of three to facilitate rapid screening, in 13 separate trials. In each trial, 200 g of the treatments and the control (non-flavoured barley) were placed in separate feeding trays spaced approximately 5 m apart in (6 x 30 m) possum pens. For each of four nights, the treatments were rotated one position to overcome any bias caused by possums having preferred feeding sites. Six replicates of the treatments were set up: two in each of three pens, each containing 10-20 possums.

Weights consumed of each treatment were recorded daily and expressed as a percentage of the quantity offered. The data were analysed by two-factor (i.e. flavour:night) ANOVA and Duncan's Multiple Range test after normalising the data using an arcsin-square-root transformation. This analysis was restricted to comparing flavours used in the same trial. Ranking preferences for flavours from all trials was done by dividing the mean consumption of each flavour by the mean consumption of the non-flavoured barley against which it was tested.

Flavours subsequently selected for testing as masks were cinnamon and orange. For carrot baits, cinnamon was applied in the surface solution of 1080 at 0.1% wt/wt bait. For pellets, both cinnamon and orange were incorporated with the 1080 during manufacture, at 0.1% and 0.125% wt/wt respectively.

Bait toxicity. Assays indicated that non-flavoured and flavoured carrot bait treatments contained similar concentrations of 1080 (0.14% and 0.13% wt:wt respectively), and non-flavoured and flavoured pellet bait treatments were also similar (0.18 and 0.17% wt:wt).

Innate aversion mechanisms and evaluation of behavioural response to baits. Both the mechanisms of innate aversion toward 1080 baits and the success of masking 1080 poison with flavours were examined by firstly determining whether baits were rejected by smell (i.e. no baits eaten) or taste (i.e. small part of a bait eaten) in the initial response period. Caution in investigating baits was equated with the time that lapsed after a possum emerged from the nest box until it started eating the first bait (i.e. response time). Subsequent caution in eating toxic baits was measured by the time spent feeding on the bait and the number of baits eaten in the minimum latent period (i.e. the time before 1080 affected behaviour). Overall preferences for toxic bait treatments were assessed from the quantity of baits eaten and time spent feeding on them throughout the entire period of each test. Time spent eating baits was estimated for baits eaten after the observation period from the mean time taken to eat baits during observations.

Non-parametric methods were used for data analysis as data were not normally distributed and none of the transformations used normalised all data. Pair-wise comparisons were made between treatments rather than analysing data factorially because the experimental design was non-orthogonal (it lacked the non-toxic and toxic carrot-orange treatments). Comparisons of median values were made by the Rank Sum test. Proportions were analysed by the chi-square test with Yates' correction for small sample sizes (i.e. <200) (Sokal & Rohlf 1973). Comparisons of treatments with and without either 1080 or flavour were made using one-tail tests as in each case a particular outcome was expected; all other comparisons were made using two-tail tests.

5.2.2 Results

Innate aversion to non-flavoured baits. After emerging from the nest boxes, possums fossicked around their pens, locating baits only when they were within approximately 0.5 m. Of 162 possums tested, only one possum (offered toxic pellet) was not observed or recorded, from partly eaten baits, as having encountered baits.

Innate aversion towards toxic baits was clearly evident (Fig. 5.1). Only 7% of possums rejected non-toxic carrot (by smell or taste), but 27.5% rejected toxic carrot baits ($\chi^2 = 6.00$, $P < 0.05$) and therefore survived. Similarly, only 5% of possums rejected non-toxic pellets, but 34% rejected toxic pellets ($\chi^2 = 10.52$, $P < 0.01$). The survivors of toxic carrot tests were approximately equally divided into those that detected 1080 by smell (45%) and those that detected by taste (55%). More survivors (79%) of toxic pellet tests had detected 1080 by taste, but the difference was not statistically significant ($\chi^2 = 1.63$, $P = 0.20$).

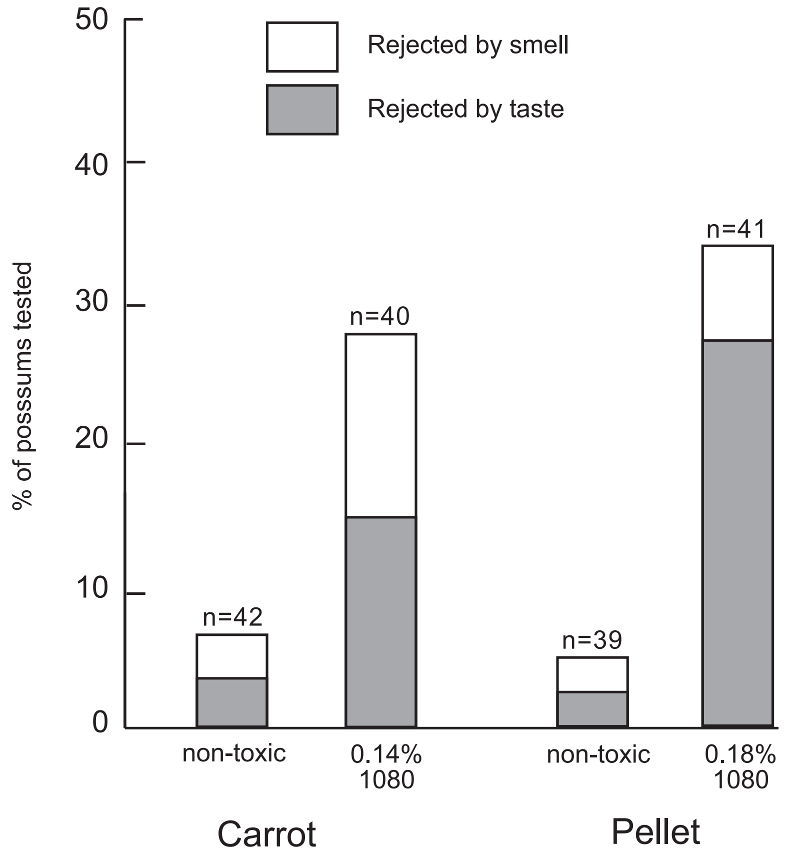


Fig. 5.1 Observed rejection responses of captive possums to non-toxic and toxic carrot and pellet baits. (From Morgan 1990a).

Disregarding those animals that refused baits by smell, possums were significantly more cautious about tasting toxic pellets (median time to first bite = 340 s) than non-toxic pellets (79.0 s) ($P < 0.05$). However, the difference in median time before tasting toxic (265.5 s) and non-toxic carrot baits (284.5 s) was not significant ($P > 0.05$).

All baits were eaten in 26% of the non-toxic carrot trials and in 23% of the non-toxic pellet trials, confirming that there was no difference in preference for either type of non-toxic bait.

Flavour trials: in all 13 flavour trials, the order of possums' preferences for the three flavours and for the control treatment remained consistent over the four-night trial, with no significant night:flavour interaction found in any of the trials.

Only one type of flavoured barley, orange, was preferred to non-flavoured ($P < 0.05$). Of the 39 other flavours tested, 19 had no effect on barley consumption, and 19 were less preferred

(*P* < 0.05) than non-flavoured barley (Fig. 5.2). Orange was therefore selected for testing as a mask for 1080. Cinnamon was also tested because it ranked fourth, and is repulsive to some bird species (Pracy *et al.* 1982).

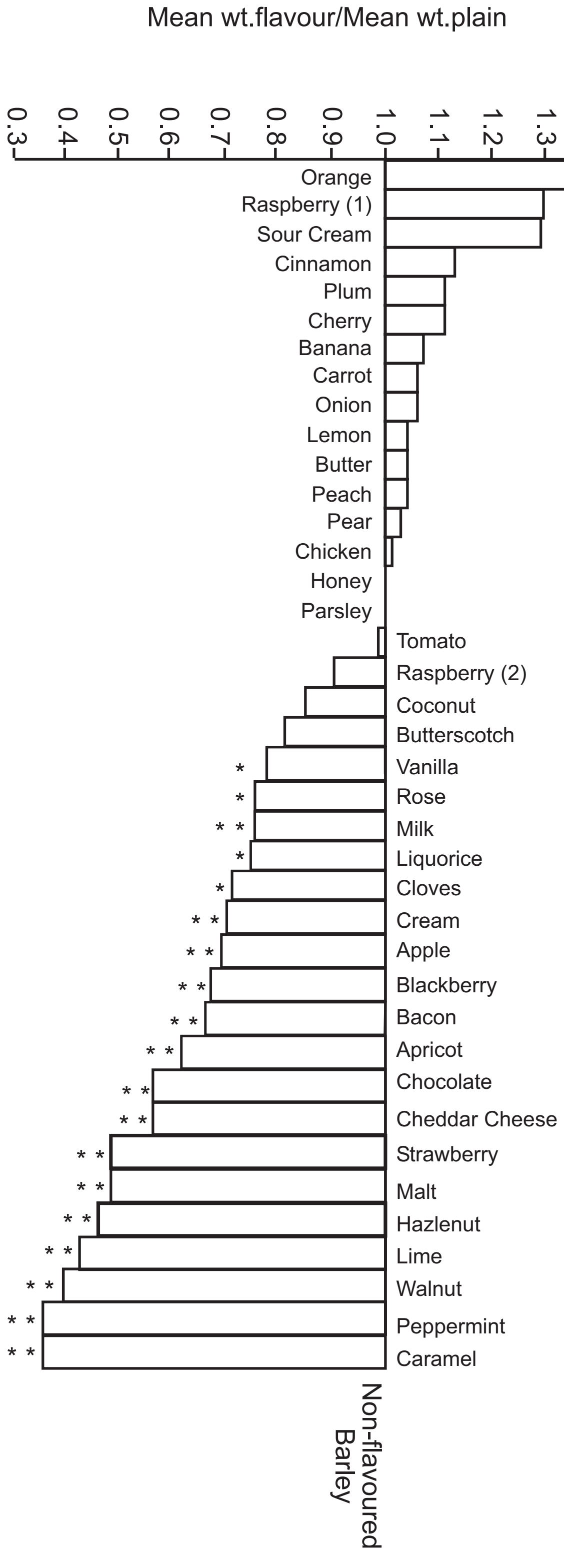


Fig. 5.2 Ranking of flavours for preference by captive possums. Asterisks indicate a significant difference between the mean weights eaten of flavoured and non-flavoured barley at probability levels * = $P < 0.05$ and ** = $P < 0.01$. (From Morgan 1990a).

Innate aversion to flavoured baits (effects of masking): Rejection of toxic baits was overcome by the addition of cinnamon or orange flavours (Fig. 5.3). Both toxic carrot baits and pellets with cinnamon were accepted at least as well as the non-toxic equivalents (χ^2 = 2.07, *P* = 0.15; χ^2 = 0.0, *P* = 1.0 respectively). Toxic pellets treated with orange were also accepted as well as non-toxic equivalents (χ^2 = 0.0, *P* = 1.0). The small degree of refusal of non-toxic flavoured baits was similar to the 5% and 7% refusal of non-toxic, non-flavoured pellet and carrot baits respectively (Fig. 5.1).

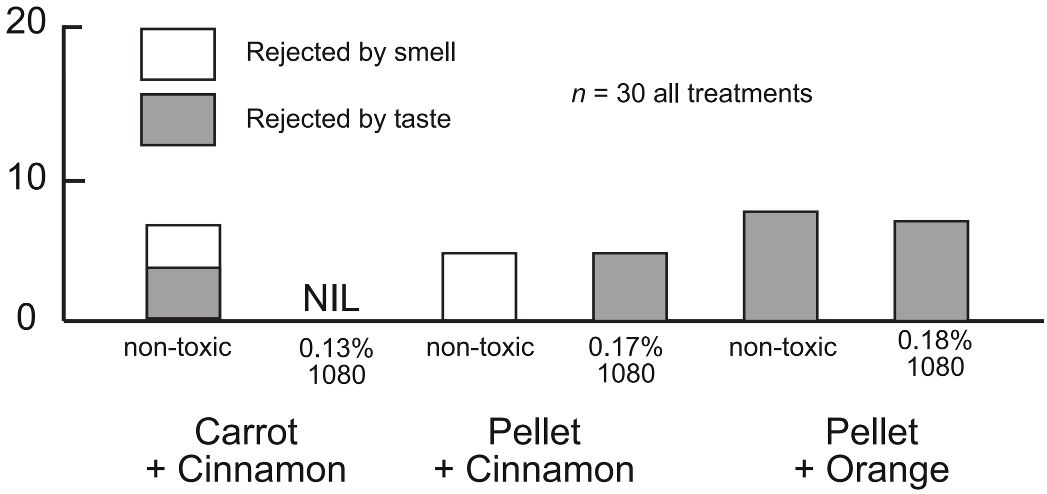


Fig. 5.3 Observed rejection responses of captive possums to non-toxic and toxic carrot and pellet bait masked with either cinnamon or orange oil. (From Morgan 1990a).

Inclusion of flavours had no statistically significant effect (*P* > 0.05) on the time until baits were first tasted, despite some considerable differences in median values. Individual possums had highly varied responses. For example, although cinnamon-flavoured toxic pellets were tasted after a shorter median time lapse (1 min 43 s) than non-flavoured (5 min 40 s) toxic pellets, the range of values for individual possums varied from 1 s to 2 h 5 min for flavoured and from 1 s to 1 h 29 min for non-flavoured pellets.

Possum behaviour in toxic tests showed a marked change as the 1080 started to take effect. Typically, the possum would stop feeding and either return to a nest box or seek an alternative secure resting place such as a high point or a corner of the pen. The median latent period to the first observed response was 31 min 30 s (range 10-120 min) after the first bite of toxic carrot bait and 63 min (range 40-165 min) after toxic pellet bait, which was significantly longer ($P < 0.001$).

The time until death was confirmed for only 62% of the observed possums as some died between the completion of observations and the following morning. For the timed deaths, the median time after eating toxic carrot (12 h) or toxic pellets (14 h) did not differ significantly, nor did the median number of baits eaten by possums that died differ. Males and females were equally as likely to survive exposure to either toxic carrot or pellet baits and there was no significant difference in the proportion of juveniles and adults that survived.

The latent periods for toxic-cinnamon baits were similar to the values for equivalent non-flavoured baits, and the difference between pellet and carrot persisted with cinnamon flavouring ($P < 0.001$). The time until death after eating cinnamon toxic pellet was longer than for cinnamon carrot bait ($P < 0.01$) despite the quantities of 1080 ingested being not significantly different. For orange toxic pellets, only about half the amount of 1080 contained in cinnamon carrot baits was ingested and median time until death was longer than for cinnamon carrot baits ($P < 0.05$).

There were no significant differences in the times until death for flavoured and non-flavoured baits, whether pellet or carrot, and so data for flavoured and non-flavoured treatments were log-transformed to normality and pooled to examine the relationship between the number of baits eaten and time until death. There was a significant correlation for carrot baits ($r = 0.42$, $P < 0.01$) but not for pellet baits ($r = 0.2$, $P > 0.05$).

Reaction to 1080 poisoning: The only observed signs of poisoning common to all tests in which toxic baits were offered were the onset of a progressive lethargy after the initial latent period and deteriorating coordination until death. However, as observations were concentrated on the first few hours after possums encountered bait, it was not possible to fully document the effect of 1080 on possum behaviour. Retching was seen in only nine (5%) of the toxic tests observed, and this was at a median time of 51 min after the first toxic bait was eaten (range 40-200 min, data from all toxic treatments pooled). Vomiting was seen only in three (2%) toxic bait tests (two with plain pellets, one with orange pellets), and it occurred at a median time of 73 min (72-84 min). In all but two of the tests in which retching or vomiting occurred, the affected possums had eaten more than the median number of baits consumed by all possums offered the particular treatment, and only one of the 12 possums survived. In the later stages of poisoning, a few possums shivered, breathing occasionally became rapid, some males ejaculated, and all became unresponsive to disturbance. No possums were observed convulsing or were heard emitting unusual sounds. Of the possums that survived sublethal poisoning, most took 1 or 2 days to recover appetite and normal activity.

5.2.3 Conclusions

Survival of 27.5% of the possums offered 0.14% toxic carrot baits indicates that aversion to 1080 was an important reason for possums surviving 1080 control operations when similar baits were used. The result from the captivity trials is consistent with the 27% that survived 0.2% bait in the Wainihinihi field trial (see section 2.5.3), suggesting that the captivity trials closely modelled the field situation. Since the pellets used proved more toxic (0.18%), it is less certain that the 0.15% pellets used in routine operations would have been as aversive. However, aversion was greater in the pellet trials than in the carrot trials, and more than one-third of possums survived the pellet trials. Therefore, it seems most likely that effectiveness of past pellet-poisoning operations was also reduced by aversion to 1080.

Survival rates of this order would greatly reduce the effectiveness of control operations as the time for recovery of the population is reduced exponentially. Carrot and pellet operations between 1971 and 1977 in which no masking flavours were used achieved an average kill of 73% (Batcheler 1978). Spurr (1981) predicted that where control achieves a 95% kill, the population would recover to within 5% of the original level within 18 years, assuming a maximum annual rate of increase of 40%. If, however, 27.5% of possums survived past carrot-baiting operations, in which baits were usually of similar toxicity to those used in this study, then the predicted equivalent recovery time from a 72.5% kill would fall to 11 years. Thus, although possums may have survived for other reasons, such as gaps in bait distribution, behavioural aversion to 1080 baits will substantially reduce the recovery time for the population. Further control would therefore be required sooner, increasing the cost of control in the long term.

The most significant finding of this study of relevance to future control operations was that both cinnamon and orange proved to be suitable flavours for overcoming possum aversion to 1080. The two toxic levels present on the carrot and pellet baits were both effectively masked by these flavours. Toxic cinnamon carrot and pellet baits were preferred to toxic orange pellets during the initial 10 min of feeding on bait, and over the duration of the trial toxic cinnamon carrot bait was the most preferred bait, but all three flavoured toxic treatments overcame aversion towards non-flavoured toxic bait. As all three toxic bait types are likely to be equally effective, other factors such as cost, quality, availability, ease of handling, shelf-life, and aerial sowing characteristics become more important in selecting bait for control operations. These trials have shown that the use of cinnamon or orange is an inexpensive solution to the costly problem of innate aversion to 1080 baits.

These results indicate that possums use both smell and taste to evaluate new foods in a highly effective manner. Only one other study (Sinclair & Bird 1984) has documented behavioural aversion by a mammal to a 1080 bait on first encounter: the marsupial *Sminthopsis crassicaudata* used smell and taste to avoid eating lethal amounts or 1080 meat baits used for dingo control. After readily eating non-poisoned meat baits for 3 weeks, when 1080 was added, 25% of the population refused toxic meat and most eaters reduced their intake. When non-poisoned meat was again offered, those that had refused once again ate the baits indicating that the senses of smell and taste were used continually to screen food, even once it had become familiar. This may, however, demonstrate a more general caution towards changes in the quality of a familiar food rather than innate detection of a harmful substance. However, my finding that many possums are innately averse to 1080, without any prior conditioning to bait, suggests a strong, genetically based behaviour. While physiological adaptation to fluoroacetate has been demonstrated for many marsupials that have coevolved with plants containing fluoroacetate (Oliver *et al.* 1977), my findings suggest that many possums have a genetically based, innate behavioural aversion to 1080. For this to have developed implies, firstly, that the Australian forbears of New Zealand possum populations must have coevolved with such plants to render the behaviour adaptive, and secondly therefore, a wider distribution of these plants than exists today (since the plants are absent today in areas from which original stock were introduced). Possums' evaluation of new foods may also be influenced by maternal influences before juveniles reach independence as this is known to occur in rats (Galef 1990) and rabbits (Walters & Bloomfield 1991). Juvenile possums spend several months as 'backriders' and would therefore often be in close proximity to both the mother and foods she selected.

Possums that ate toxic pellet baits showed a latent period roughly twice as long as that for toxic carrot baits, despite the higher toxicity of pellets and larger amounts of 1080 ingested. Time until death was also significantly longer after consumption of cinnamon pellets than cinnamon carrot, even though similar amounts of 1080 were ingested. These results further demonstrate the influence of bait type on the toxicity of 1080 reported by O'Brien *et al.*

(1988) and Henderson *et al.* (1999a). The higher content of sugar in pellets may delay 1080's progressive restriction of the energy supply. If bait distribution is sparse in control operations, a longer latent period could be exploited to ensure that more possums find a lethal quantity of bait. Extension of the latent period, therefore, by addition of sugars may be a useful technique for avoiding sublethal poisoning in control operations.

5.2.4 Contemporary review of the study and its findings

The findings of this study were extensively promoted (e.g. Morgan 1985) to ensure rapid uptake by possum managers. This resulted in the adoption, in the late 1980s, of cinnamon as the standard mask to be included in manufactured pellet baits and added to the 1080 solution applied to chopped carrot. While this has addressed one of the reasons for possums surviving control operations, recent research has shown that cinnamon concentrations decline over time, so that the effectiveness of masking also declines (Henderson & Frampton 1999). To retain adequate masking, it is now recommended that cinnamon concentration is doubled (to 0.2% vol:wt) in pellet baits and trebled (0.3% vol:wt) on carrot baits to allow for the effects of shelf-life and field-life of baits (Henderson & Frampton 1999).

Since cinnamon has now been used extensively in possum control for 15 years, there is some concern that many survivors of control operations may learn to recognise its distinctive smell and associate it with toxicosis. While research has shown that cinnamon is a relatively unimportant cue in the development of such learned aversion to 1080 baits (see Chapter 6), it is nevertheless prudent to utilise other masks in successive control operations. This study demonstrated a number of alternative favoured flavours, including orange, plum, and cherry. Among other flavours that led to increased consumption of barley in my trials, sour cream flavour is not particularly strong-smelling and hence may prove less effective as a mask, and raspberry is not recommended because field trials indicated that it was a major factor in the extensive mortality of birds recorded after several NZ Forest Service aerial operations conducted in the mid-1970s (Batcheler 1978).

Research on taste/flavour masking has also advanced considerably in recent years providing opportunities for the use of alternative approaches to masking 1080 poison. For example, microencapsulation is now routinely used to mask the undesirable taste of many human drugs and to optimise the release of the compound for maximum effect (e.g. Al-Omaran *et al*. 2001), and research has begun on the masking of vertebrate pesticides for possum control (e.g. Morgan *et al*. 2001a). Taste perception results from the stimulation, in varying proportions, of four types of receptors that indicate sweetness, sourness, saltiness, and bitterness (Guyton & Hall 2000). While the chemical similarity of 1080 to acetic acid is thought to give the compound a sour taste like weak vinegar (Eason & Wickstrom 2001), it is likely that receptors of the other tastes are involved in creating an overall taste sensation. Inhibitors for human taste receptors (e.g. Roy 1997), and taste-modifying proteins with extreme sweetness (Witty 1998), also provide further potential means of interfering with possums' recognition of 1080.

Complete elimination of a possum population is more desirable than a high level of control since the recovery time will be much slower, being dependent on immigration alone. Possums' responses to non-toxic baits in this study confirmed the findings of earlier bait acceptance field trials (section 2.5) in which, typically, around 5% of possums refused non-toxic bait. This provoked further research (reviewed in Chapter 7) to achieve complete elimination through investigation of factors influencing bait palatability and the use of prefeeding to overcome neophobia, resulting in 'best practice' advice to pest managers. Additionally, it suggested that the use of neuroactive substances (termed 'appetite enhancers') to modify feeding behaviour may help overcome survival resulting from taste aversion to 1080 baits. Several neuroactive compounds had been shown to increase food consumption in rats and rabbits (Cook & Dean 1996; Devine & Cook 1998) and I tested these in possums to determine if an increase in mean consumption during the first 30 min of feeding (i.e. before the onset of toxicosis) would occur (Morgan *et al*. 1999; Morgan & Devine 2001). However, no such effect was detected in possums during this short period, nor over a period of several days for which food consumption was measured. I had also previously found possums to be insensitive towards hypnosedative tranquillisers (i.e. Fentaz, Tryptanol, Trilafon, Melleril, Librium, Stresnil, and Valium) in the treatment of post-capture stress. It would therefore appear that there may be some major differences in the manner in which the possum, and perhaps other marsupials, metabolise such compounds, as has been reported with respect to the possum's insensitivity to paracetemol compared with placentals (Eason *et al*. 1999). Such differences may, for example, result from differing rates of absorption from the intestinal tract or differences in the binding sites or mechanisms in brain tissues of the two groups of mammals. Differences in eutherian and marsupial metabolism may prove a fruitful area for development of target-specific toxicants, as has already begun in relation to the possum's unusual water-regulating mechanism in the the lower intestine (B. McLeod *pers. comm*.).

This study identified a major reason for possums surviving aerial 1080 poisoning operations (i.e. innate aversion to 1080) and a practical solution (i.e. masking). However, growing evidence of a range of rodents developing bait shyness in control operations using a variety of toxicants (eventually summarised in Prakash (1988)) suggested that possums may, if they survived after eating 1080 baits, be capable of learning to avoid eating further baits. I therefore carried out research, detailed in Chapter 6, on the ability of sublethally dosed possums to learn to avoid eating baits containing either 1080 or other poisons used by pest managers to sustain the benefits given by initial aerial 1080 baiting operations.

Chapter 6. Learned Aversion Towards Toxic Bait, Its Mitigation and Options

6.1 Introduction

In this chapter I summarise new research conducted during 1995-2002 (i.e. mainly during the term of my thesis enrolment) that examined possums' ability to learn an aversion towards toxic baits, and review the management implications of the findings.

Maintaining possum populations at densities low enough to avoid agricultural or conservation impacts necessitates repeated control operations. Where baits containing acute (fast-acting) toxicants have been used repeatedly against pest rodent species, efficacy typically declines as a result of the animals developing a *learned aversion* to the bait (Prakash 1988). This behaviour, also referred to as *bait shyness*, *conditioned aversion* or *conditioned avoidance* (see review by Riley & Clarke 1977), results from an unpleasant experience after consumption and assimilation of a sublethal quantity of toxic bait (Nachman & Hartley 1975). The animal associates that experience with the bait eaten and quickly learns to avoid further consumption. Learned aversion has been considered the predominant mechanism in animals' selection of natural foods (Rogers 1978), and chemicals that cause mammalian herbivores to avoid or limit food intake have been identified (e.g. Pass *et al.* 1998; Reichardt *et al.* 1990). The strength of learned aversion in rats is dependent on the latency of the toxicant (i.e. the lag phase) (Andrews & Braveman 1975) but the degree of sickness induced does not influence the strength of aversion (Nachman & Hartley 1975),. This may be due to different physiological mechanisms mediating the sensations of illness (Barnett *et al.* 1975), with stimulation of the emetic system of the brain stem being a likely prerequisite (Garcia 1989). For example, sub-lethal doses of strychnine and cyanide both cause overt illness in rats but do not induce bait shyness (Nachman & Hartley 1975), probably because they directly affect the nervous system and metabolism rather than the emetic system (Hayes & Laws 1991).

It cannot be assumed, however, that possums have the same tendency to develop bait shyness as rodents since data on the comparative learning ability of possums and eutherian mammals are conflicting. For example, possums performed as well as carnivores, skunks and three species of monkey in learning to respond to varying position and light as cues for a reward (Kirkby & Williams 1979), but were less successful than cats and rats in learning to negotiate mazes based on visual and tactile cues (Pollard & Lysons 1967). Furthermore, the Virginia opossum (*Didelphis virginiana*) performed poorly in a reward-based test of ability to learn to discriminate between the presence or absence of an odour (Tilley *et al.* 1966). Nevertheless, a strong suspicion that possums can learn to avoid baits was provided by empirical observations made by Hickling (1994) who noted declining kills in three successive, annual control operations (75%, 30% and 0%) at Mapara Forest in the central North Island. He also conducted field experiments which confirmed that, among populations previously exposed to rabbit baits containing only 0.02% 1080, a high proportion of possums developed bait shyness, at least in the short term. Although strongly suggestive of bait shyness, these observations warranted confirmation in a controlled experiment. It was also necessary to investigate the possible development of bait shyness resulting from the use of other poisons in maintenance control operations because, in New Zealand, this is common practice between aerial operations. In the long term, aerial 1080 poisoning in any particular area will continue to be successful only if it is integrated with compatible, interim maintenance control techniques that do not generate persistent, behavioural resistance towards 1080 baits. Further information was needed on which to base the development of such long-term control strategies for sustained control.

In this chapter, I summarise a series of studies designed to provide some of this information, review other relevant studies, and draw comparisons with information on bait shyness in rodents. In my experimental work, I examined: (1) the development of bait shyness in caged possums following consumption of sublethal baits containing either 1080, cholecalciferol, cyanide, and brodifacoum, (2) the persistence of bait shyness induced by 1080 and cyanide, and (3) ways of mitigating learned aversion by changing bait characteristics.

6.2 Cage trials to assess bait shyness

The work has been presented in detail elsewhere: Morgan *et al*. (1996a), Morgan & Ross (2001), Morgan *et al*. (2001b), and Morgan & Milne (2002). A summary is presented here to emphasise the key findings that relate to the sustainability of aerial 1080 poisoning operations.

6.2.1 Methods

Possum capture and husbandry. Possums were captured in the Waipara Gorge district of North Canterbury (see Appendix 1 for coordinates) using metal box traps baited with apple.

There was no history of 1080 usage in this area. After transfer to the Landcare Research animal facility they were housed in individual cages (530 x 400 x 1000 mm) that contained nest boxes (230 x 200 x 350 mm), and were maintained on a diet of fruit, vegetables, and supplementary feed pellets. Drinking water was continually available. The animals were acclimatised to captivity for at least 4 weeks, as recommended by Day & O'Connor (2000). Ambient temperature was maintained within the range 18-22°C, and lighting on a 12:12 h light:dark cycle, with complete refreshment of air every 4 min. Possums were routinely weighed at least weekly to assess general health, enabling estimation of doses (i.e. mg/kg body weight) of toxicant ingested.

Toxicants. Four toxicants, all registered for possum control in New Zealand, were used in combination with different bait types as described below. The toxicants differ in their mode of action and in their speed of action, ranging from the very rapid acting cyanide to the very slow acting anticoagulant toxicant, brodifacoum (Table 6.1). Speed of action of toxicants was considered to be an important characteristic of toxicants in determining the possum's ability to learn aversions towards toxic baits.

Table 6.1 Approximate timing of the effects of the toxicants used with possum baits to assess bait shyness (and sources of data as indicated)

	Sodium or potassium cyanide	1080 (sodium monofluoroacetate)	Cholecalciferol (vitamin D_3)	Brodifacoum
Mode of action (from Eason & Wickstrom 2001)	Inhibits respiratory uptake of oxygen	Inhibits conversion of citrate in the Krebs cycle, and hence, energy production	Induces hypercalcaemia, and mineralisation of blood vessels	Inhibits production of blood clotting enzyme
Mean times (from O'Connor *et al* 2003) until:	(Minutes:seconds)	(Hours:minutes)	(Days)	(Days)
- first signs of sickness	3:09	1:52	2	13 (decline in feeding)
- loss of responsiveness	6:27	At death	Just before death	2 h before death
- death	17:55	11:26	9	21

Testing for induction of bait shyness. Possums were randomly allocated to treatment groups with approximately equal sex ratios. Dose rates and presentation matrices are summarized in Table 6.2.

Table 6.2 The sublethal doses of four toxicant-bait combinations presented to possums, and the resultant mortality.

Toxicant	Bait type	Actual (and nominal) concentration of toxicant in bait (% wt:wt)	Sublethal dose given (mg/kg)	No. possums dosed	Mortality (%)
1080	Cereal pellet with cinnamon	0.13 (0.15)	Low = 0.4	42	0
			High = 1.0	89	36
Cholecal-ciferol	Cereal pellet with cinnamon	0.84 (0.8)	Low:		
			females = 2.5	30	0
			males = 4.3	34	12
			High:		
			females = 6.7	23	35
			males = 8.5	16	44
Cyanide	Paste covered with sweetened flour	53.9 (55.0)	Low = 2.2	24	0
			High = 5.9	36	0
Brodifacoum	Cereal pellet with cinnamon	0.0025 (0.002)	High = 0.3	22	41

1080 and cholecalciferol were presented in ‘low’ and ‘high’ sublethal doses in cereal pellet baits (Animal Control Products, Waimate) flavoured with cinnamon as a toxicant mask (Morgan 1990b). Brodifacoum, presented in the same cereal pellets, was used only in a high sub-lethal dose as bait shyness was not expected on the basis of rodents’ responses to this toxicant (Prakash 1988). Cyanide, incorporated in a petrolatum-based paste at a nominal concentration of 55% wt:wt (Animal Control Products, Wanganui), was presented in low and high sublethal doses with orange-flavoured, sweetened flour as an attractant, as is standard field-practice. Samples of all baits were assayed for toxicant concentrations so that known doses of bait could be presented to possums. The low and high doses given corresponded approximately to LD_{10} and LD_{40} values based on a published dose-response curve for 1080

(Henderson *et al.* 1999a) and linear extrapolation from published LD_{50} data for cholecalciferol (Jolly *et al*. 1995), cyanide (Bell 1972), and brodifacoum (Eason *et al.* 1994). Different doses of cholecalciferol were given to males and females because the sexes are known to differ in their susceptibility to this toxicant (Jolly *et al.* 1995). The choice of doses aimed to represent approximately the range of sublethal doses that most possums surviving control operations may have ingested. These tests resulted in some mortality on each occasion and a consequent decline in sample size. At each time point therefore, the sample sizes were increased by the proportion of possums killed at the previous time point as it was assumed that these (non bait-shy) possums would have been killed if they had been included in the test.

Baits containing cyanide, 1080, or cholecalciferol were presented for 16 h overnight, while the slower-acting brodifacoum baits were made available for 4 days. Possums that did not eat the portions of 1080 bait (Fig. 6.1) containing these doses (i.e. those considered innately bait-shy) were removed from the experiment at this stage to maintain the focus of the study on learned bait shyness. Surviving possums' appetite was recorded to monitor their return to full health, and they were then presented with a lethal quantity of the same bait/toxicant offered initially. This was after 7 days for cyanide and 1080, 21-30 days for cholecalciferol, and 34 days for brodifacoum. Four groups of naïve possums (i.e. individuals not previously exposed to sublethal baits) were also presented with baits containing the different toxicants. Bait shyness in survivors was defined as consumption of less than 1 g of bait by surviving possums, as some possums use taste as well as olfactory and visual cues to recognise baits (Morgan *et al.* 1996a). The relationship between the percentages of possums showing shyness and toxicant, dose (i.e. low or high sublethal dose), and experience (i.e. initial versus subsequent exposure), was investigated using logistic regression in S-Plus 6 (S-Plus 2001). This model was fitted by maximum likelihood estimation and likelihood ratio tests were used to assess the significance of these factors.

The persistence of bait shyness towards 1080 baits was further tested in low-dose-group possums at 90 days (high-dose possums being used in 'bait-switching' tests – see below), and in combined low- and high-dose groups at 365 and 730 days. The persistence of bait shyness towards cyanide baits was retested in combined low-dose and high-dose groups at 90 and 300 days.

Overcoming bait shyness by 'bait-switching'. Different combinations of bait type, toxicant, and flavour (Table 6.3) were presented to groups of bait-shy possums to determine if shyness could be overcome by changing the cues by which possums recognised baits. Groups comprised approximately equal proportions of survivors from low- and high-dose groups for cholecalciferol and cyanide, while only high-dose survivors were used (i.e. those expected to be most shy) in the first of these studies using 1080. Since a full assessment of the importance of each of these bait factors (and their interactions) would have been prohibitively costly, a few practical options (i.e. bait formulations that were already registered for use) were tested for overcoming bait shyness. Lethal quantities of alternative baits were therefore presented between 35 and 100 days after initial baits were eaten, and shyness assessed as described above. The percentages of groups shy to initial baits were confirmed before bait-switching by either: (1) testing a separate group (1080), (2) testing all possums selected for bait-switching (cholecalciferol), or (3) testing a subsample of those selected for bait-switching (cyanide). Due to the restricted design of these experiments, statistical analysis of these data was not possible. Instead comment is made on which options were most successful.

6.2.2 Results

Testing for induction of bait shyness. The low and high sublethal doses of 1080 and cholecalciferol given resulted in sufficiently similar mortalities (low: 0-12% and high: 35-44%) (Table 6.2) to permit comparison of the bait shyness induced. Comparison with cyanide-induced shyness must be made with caution since no possums were killed by the estimated LD_{15} and LD_{40} doses of cyanide, indicating that Bell's (1972) LD_{50} overestimated lethality.

Bait shyness was caused by sublethal doses of all three fast-acting toxicants, cyanide, 1080, and cholecalciferol, but no bait shyness was found after possums ate sublethal doses of the slow-acting brodifacoum (Fig. 6.1).

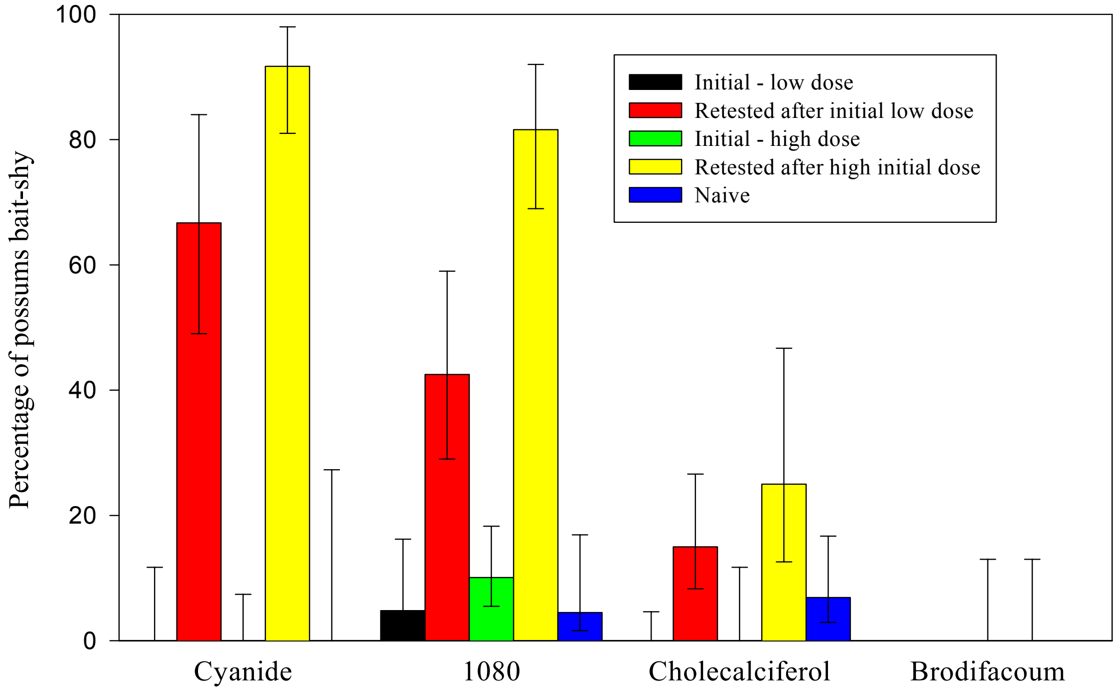


Fig. 6.1 The percentage of possums that were bait-shy on initial presentation of either low (approx. LD_{15}) or high (LD_{40}) sublethal doses, on retesting after these doses, and in control groups of naive animals offered free access to baits, on first exposure. Sample sizes varied between 22 and 64. The treatments follow the same sequence as shown for 1080 (enabling interpretation where zero values, and hence no colouring, are shown). Brodifacoum baits were not used at a low initial dose or among naive possums for assessing shyness as no shyness was expected or found, even at the high sublethal dose tested. Vertical bars indicate binomial 95% confidence limits.

Detailed statistical analysis was performed on all three factors (toxicant, experience, and dose) for all toxicants except brodifacoum as it did not induce bait shyness in any possums. The percentage of possums becoming bait-shy was strongly influenced by dose (χ^2 = 16.9, d.f. = 1, P < 0.001) independently of toxicant (χ^2 = 2.42, d.f. = 2, P = 0.30) and experience (χ^2 = 0.40, d.f. = 1, P = 0.53): higher initial doses resulted in greater shyness. The type of toxicant used also affected the proportion becoming bait shy, but this was dependent on experience (χ^2 = 2.81, d.f. = 2, P = 0.001) due to the different responses to 1080. Among naive animals, 5% were innately shy towards 1080cinnamon-masked baits, consistent with the earlier results of a pen study (Fig 5.3), and 7% were innately shy towards cinnamon-masked cholecalciferol baits to cyanide or brodifacoum. In contrast, no naive animals were innately bait-shy for the other toxicants. Shyness in experienced animals was much lower for brodifacoum (0%) and cholecalciferol (18%) than 1080 (62%) and cyanide (82%) baits. There was no evidence for a three-factor interaction between the three factors (i.e. toxicant, dose, and experience) ($\chi^2 = 0$, d.f. = 2, $P = 1$).

Persistence of bait shyness. Bait shyness towards cyanide and 1080 baits declined significantly during the first 90 days (as indicated by non-overlapping confidence intervals, Fig. 6.2). Thereafter, however, most possums that were bait-shy at day 90 remained bait-shy for the duration of each study (i.e. 1 year for cyanide, and 2 years for 1080) suggesting that they probably would have remained bait-shy even longer. The decline of shyness appears more rapid for 1080 than cyanide (Fig. 6.2), but the data are too limited to confirm this statistically, and bait shyness at day 90 was probably underestimated for 1080 because only possums from the low-dose group were retested at this time.

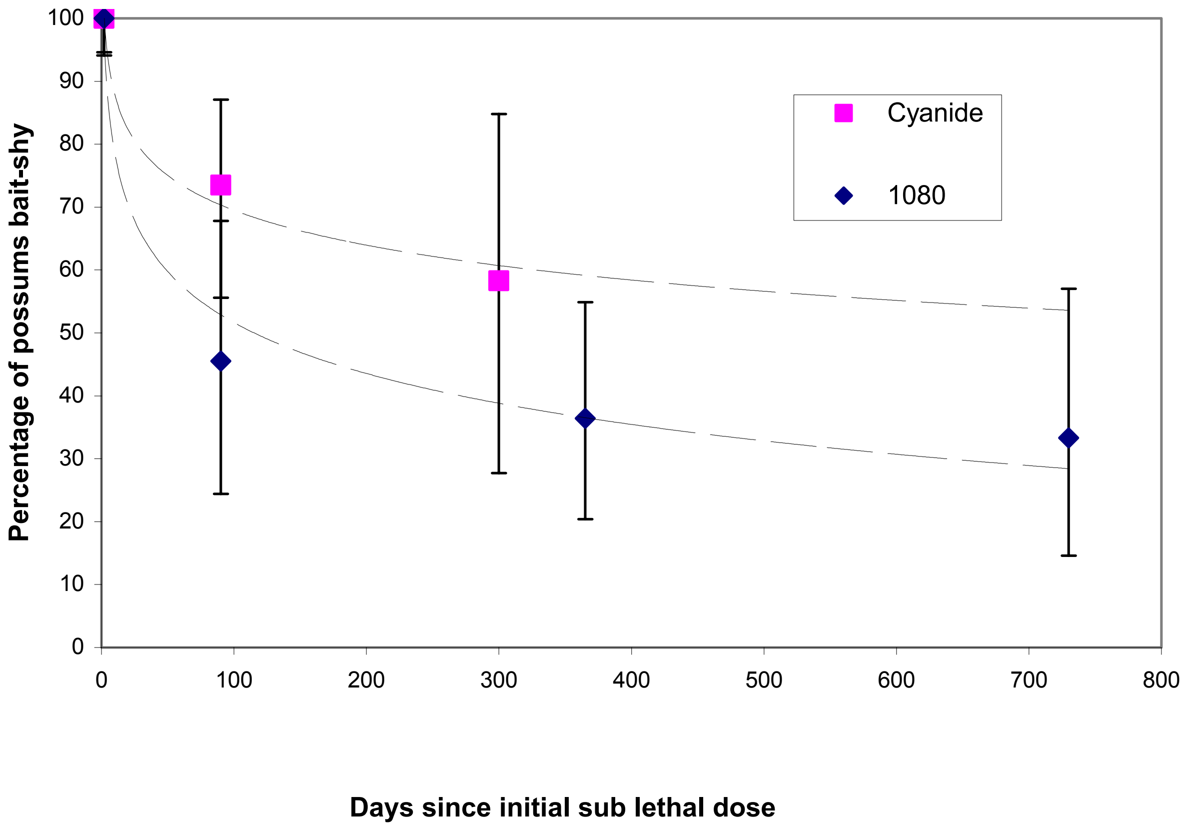


Fig. 6.2 The percentage of surviving possums estimated as bait-shy after different time intervals following consumption of sublethal doses of bait. Vertical bars indicate binomial 95% confidence limits. Estimates at each time point are based on sample sizes that were

corrected proportionally for mortalities recorded at previoustime points. The trend lines are fitted by eye.

Overcoming bait shyness by bait-switching. For each toxicant, the mean initial doses consumed by possums used in bait-switching tests were similar, rendering the effectiveness of alternative baits comparable (Table 6.3). Although cyanide induced the highest proportion of bait shyness initially, it was most readily overcome by bait-switching using three types of bait that differed from the initial bait in all three characteristics (i.e. toxicant, bait type, and flavour). Despite the lower level of bait shyness induced by cholecalciferol, bait-switching was only moderately effective, even when all three characteristics were changed. Bait shyness induced by 1080 was effectively overcome (even though only high-dose survivors were used) by a change of bait type (to carrot) and flavour (to orange), whereas changing the flavour or toxicant alone was not very effective. This suggests that possums' bait shyness is based primarily on recognition of the bait base.

Table 6.3 The effectiveness of bait-switching in overcoming bait shyness. Bait shyness was initially induced when possums ate baits containing either 1080, cholecalciferol or cyanide, and was confirmed subsequently by their refusal of the same bait type. The effectiveness of bait-switching is indicated by the percentage of possums shy towards alternative baits. Alternative baits were presented for one night except brodifacoum pellets, which were presented for five consecutive nights.

Initial bait						Alternative bait			
Toxicant	Bait type	Flavour	Mean initial dose (mg/kg)	Days since initial dose	No. tested	Toxicant	Bait type	Flavour	No. shy (and %)
			0.73		14	1080	Pellet	Orange	11(79)
1080	Pellet	Cinnamon	0.77	90	7	Brodifacoum	Pellet	Cinnamon	3 (43)
			0.74		13	1080	Carrot	Orange	0 (0)
Cholecal-ciferol	Pellet	Cinnamon	5.48	35-45	20	Cholecalciferol	Gel	Orange	9 (45)
			5.85		20	1080	Gel	Orange	7 (35)
			8.80		22	1080	Pellet	Cinnamon	2 (9)
Cyanide	Paste and flour	Orange	9.97	100	21	1080	Paste	Apple	0 (0)
			8.85		20	Cholecalciferol	Gel	Orange	0 (0)

6.2.3 Conclusions

These studies were prompted, in part, by well-documented instances of bait shyness compromising control of rodent populations (Prakash 1988). The results suggest that possums' learning ability, with regard to poison bait avoidance, is at least as well developed as that of rats. Like rats, some possums surviving sublethal doses of acute toxicants developed a learned aversion to the bait eaten, and the proportion of possums developing such behaviour was influenced by the initial dose ingested, the toxicant used, and the latency of the toxicant. For possums, the four toxicants can be ranked for risk of causing bait shyness after sublethal dosing as follows: cyanide (~80% shy) > 1080 (~60%) > cholecalciferol (~20%) >brodifacoum (0%). This ranking corresponds with the latency of the toxicants (Table 6.1), indicating that sublethal baits containing faster-acting toxicants are more likely to result in subsequent bait shyness.

While the results bear some similarity to those reported for rodents, some interesting differences were noted. Cyanide and 1080, the most widely used toxicants in possum control, were both capable of inducing bait shyness in most possums, and this was found to be long-lived. However, although 1080 has been shown to strongly induce a bait shyness in *Rattus rattus*, cyanide was found to induce only a weak shyness in this species (Ionescu & Buresova 1977). This suggests that different mechanisms are involved in the detoxification of the cyanide in the two species, the kidney being the prime site in possums and the liver in rats (Turner 1969). Cholecalciferol was the least likely to induce bait shyness due to its slower mode of action. However, possums' development of bait shyness was stronger than that in rats. Laboratory rats were shown by Prescott *et al.* (1992) to develop a weak learned aversion to cholecalciferol baits (i.e. toxic baits were consumed less than non-toxic baits, but not avoided) reflecting both the relatively low doses given (an approximate LD_{10}) and the long latency of 13 h for this toxicant in rats (Andrews & Braveman 1975). By comparison, after eating baits with LD_{15} doses of cholecalciferol, possums not only ate significantly less toxic baits than non-toxic baits, but about 20% of possums became bait-shy, despite the relatively long latency of about 24 h for cholecalciferol in possums (Morgan & Milne 2002). It is therefore remarkable that some possums were able to associate bait consumption with the induced illness with such a delay. This suggests that different neural or metabolic mechanisms may be involved in mediating toxicosis compared with rats, possibly resulting in physiological effects occurring earlier than observed changes in behaviour.

Bait shyness in possums was extremely persistent, also exceeding that previously reported in rodents. After eating sublethal 1080 baits, 90% of caged deer mice were bait-shy 8 months later (Howard *et al*. 1977), after which the study was terminated as deer mice generally do not live this long in the wild. In laboratory rats that had eaten sublethal scilliroside (a fast-acting poison) baits, Rzsoka (1954) reported: "the memory of red squill bait may last as long as 374 days in individuals". Some possums in my cage trials remained bait-shy for at least 2 years after eating sublethal 1080 baits (although the timing of memory-loss may be more appropriately compared as a proportion of an animal's expected lifespan). Additionally, O'Connor & Matthews (1999) have shown that 18% of wild possums exposed to a 1080 control operation in the field 3 years previously were still bait-shy when tested under controlled, captive conditions. Allowing for a doubling of the residual population in the area over the 3 years (and hence approximate halving of the proportion of shy survivors), this finding is consistent with my data, which showed that about 33% of the survivors were still bait-shy after 2 years, a level expected by extrapolation to be little different at 3 years. Bait shyness in cyanide survivors appeared similarly persistent to that for 1080, and cyanide-induced food aversions have been shown in another study (O'Connor & Matthews 1997) to persist for at least 2 years. Shyness towards cyanide may have been even greater if correct LD_{15} and LD_{40} initial doses of cyanide had been used. In turn, this may have resulted in less effective bait-switching, and persistence of shyness in a greater percentage of possums. While a smaller percentage of possums developed shyness towards the slower-acting cholecalciferol baits, it is likely that shyness in these animals would be equally long-lived, but this remains to be tested.

6.2.4 Review of the management implications of bait shyness studies in possums

Bait shyness is clearly a potential threat to the long-term sustainability of poisoning as a control method. Modelling predicts that the efficacy of annual control will be reduced by >30% where bait shyness develops in 80% of survivors and persists for at least a year (Hickling 1995). Bait shyness of this order was induced by 1080 in my study. The operational cost of overcoming 1080-induced bait shyness by using brodifcoum baits was modelled by Ross (1999), and this strategy was found to cost 30% more than that needed for a population with no bait shyness. The simplest way of avoiding the development of learned bait shyness is to minimise the likelihood of possums finding and eating sublethal baits. This can be achieved by the highest standards of bait preparation and presentation, as discussed in the following chapter. Nevertheless, the possibility remains that some possums will encounter and eat only sublethal amounts of bait.

If a propensity to learn to avoid baits was a heritable trait, this could contribute to a decline in operational effectiveness in addition to the selection for both physiological resistance to 1080 and neophobic behaviour towards baits (as discussed in section 5.1). 1080 baits were consumed by, and killed, four of five naïve young of 1080 bait-shy female possums (Morgan & Milne 1997) (and the fifth possum rejected bait outright) providing no evidence that such behaviour is heritable.

Since shyness towards cyanide and 1080 baits was declining during the period when bait-switching was tested (i.e. days 35-100), effectiveness of bait treatments tested may have been overestimated. Nevertheless, the differences in proportions of possums displaying shyness to these treatments indicates which are likely to be effective in field use. The effectiveness of bait-switching in overcoming shyness differed between toxicants. For 1080 bait shyness, neither a change in the toxicant nor flavour alone was sufficient, but changing the bait base and flavour was effective, as also found by O'Connor & Matthews (1999) in a cage trial and Ogilvie *et al*. (2000) in a field trial. However, changing bait characteristics appears to be less effective in overcoming cholecalciferol-induced shyness. This may reflect the considerably longer latency of cholecalciferol, the possum's consequent inability to remember which food induced toxicosis, and a resultant generalised wariness to new foods. By contrast, bait-switching was highly effective against cyanide-induced bait shyness. However, this result differed from the results of field trials in which no additional kill was achieved by switching to either 1080 pellets (two trials) or cholecalciferol pellets (two trials) 5-25 days after populations were reduced by 60-84% using cyanide paste (Henderson *et al.* 1997). While these conflicting findings warrant resolution, it must be noted that cyanide paste has been used extensively for retrieval of possum fur for 40 years with no other reliable reports of possum control being compromised as a result. The trend towards use of an encapsulated form of cyanide, 'Feratox®' (Connovation, Auckland), may reduce the likelihood of cyanide-induced bait shyness as the small, odourless capsule is embedded in a paste bait and the cyanide is released during mastication, preventing rejection.

Alternative approaches to mitigating bait shyness include the use of prefeeding, anticoagulant poisons (i.e. a particular type of bait-switching), and traps and other killing devices. Prefeeding is done primarily to increase the effectiveness of control through familiarising pests with a bait-type before introducing the toxicant. Like black rats (Howard *et al.* 1977; Bhardwaj & Prakash 1982), possums are far less likely to develop bait shyness if they have been prefed (Moss *et al.* 1998; Ross *et al.* 2000). Presumably, they learn to identify the bait as 'safe' and are then less likely to associate it with toxicosis if sublethal baits are subsequently ingested. The benefits of, perhaps, a 10% improvement in efficacy and avoidance of bait shyness must, however, be carefully considered against the additional cost of prefeeding, which may exceed that of applying only toxic bait, depending on how many 'prefeeds' are applied.

In my cage-studies, switching to the anticoagulant brodifacoum in cereal pellets for 5 days was only partially effective in overcoming shyness to 1080 cereal pellet baits. However, in other studies, more prolonged presentation of brodifacoum, starting a fortnight after possums became 1080 bait-shy, resulted in a peaking of nightly bait intake after 14 days and a consequent mortality of 73-75% (Ross *et al*. 1997; Morgan & Ross 2001). Furthermore, in field trials, delaying the bait-switching for 2.5 months after initial control resulted in even greater efficacy (88-94% mortality; Henderson *et al*. 1997). In effect, a bait-type containing an anticoagulant acts as its own prefeed. The possum cautiously eats the bait, falsely learning that the bait is 'safe', and nightly intake increases. Although outward symptoms of toxicosis are first seen at about 13-15 days (Littin *et al*. 2000), the possum continues to consume the bait, often right up to the point of death (Morgan & Ross 2001) indicating that learned food-safety, like learned bait shyness, is a very rigid behaviour once formed. Brodifacoum baits have become regarded as a less desirable control option because they are relatively expensive, and because the toxicant is highly persistent in animal tissues posing risks of secondary poisoning. However, restricted use of brodifacoum baits in 'mopping up' populations that have already been heavily reduced by other control options is considered to be a desirable and responsible use.

Using these findings, strategies for sustained control of possums can be designed to minimise the development of bait shyness. For example, following initial control with aerially delivered 1080 carrot baits, maintenance control could then be based on the use of Feratox® cyanide baits after one year, 'long-life' cholecalciferol baits (Morgan 2003) permanently placed for the next two years, and brodifacoum cereal pellets in the fourth year. Humane kill-traps (Warburton *et al.* 2001) in the fifth and subsequent years could then be used efficiently (since they can remain in place for prolonged periods without being checked) to indicate population recovery and the need for further, cost-effective aerial 1080 poisoning once a critical population threshold is reached. There is a need to evaluate such strategies in terms of not only cost-effectiveness, but also the long-term environmental impacts and benefits.

Chapter 7. Controlling Bait Quality and Bait Delivery to Maximise Operational Effectiveness – A Review

7.1 Introduction

The earlier chapters have described my studies on biological aspects that are most likely to influence the effectiveness of aerial poisoning operations: that is, possums' feeding response to different types of baits in different habitats and in different seasons; the dispersion of baits required to ensure that possums would encounter them during normal movements over a period of a few days; and possums' ability to innately detect 1080 or to learn to avoid baits that previously contained a poison. This research led to the prediction that a very high proportion of possums in a population would, when 1080 baits are aerially distributed for the first time, consume the bait and die. However, this prediction is based on two very important prerequisites: (1) that baits are correctly manufactured to be *lethal* and *palatable* to all possums, and (2) that all possums would *encounter* such baits. The factors that influence these prerequisites for effective control are summarised in Figure 7.1. To fulfill the requirements of correct bait manufacture and delivery, it is necessary to understand the influence of these factors, and to set specifications for ensuring that they collectively maximise the chances of success.

In this Chapter I review both the research that has led to the adoption of such specifications, and the development of quality assurance procedures for ensuring that baits are manufactured and delivered in the manner desired. I wish to acknowledge the initiative taken by a colleague, Ray Henderson (formerly of Landcare Research), in leading much of the research on bait quality reviewed in this chapter.

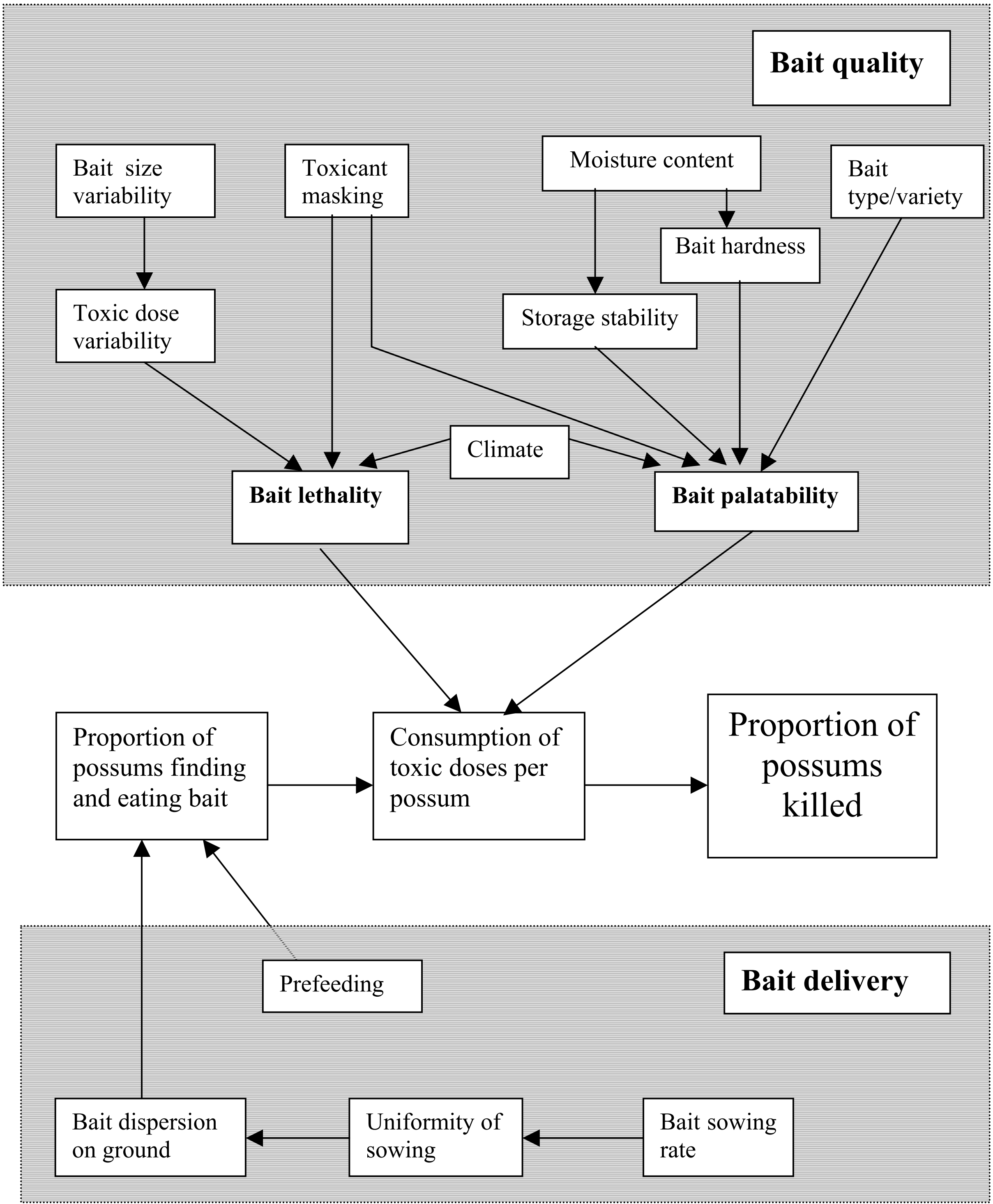


Fig. 7.1 Schematic representation showing the influence of components of bait quality and bait delivery that determine operational effectiveness. Specifications can be defined for each of the components and Quality Assurance tests used to maximise the chance of operational success. Climatic factors, particularly rain and freezing, may reduce effectiveness and are not controllable.

7.2 Components of bait quality

7.2.1 Bait lethality

For many years it has been recognised that, optimally, lethal doses of 1080 should be delivered to possums in a single bait (Peters 1975). Early data on the toxicity of 1080 to possums (Bell 1972; Rammel & Fleming 1978; Peters & Fredric 1982 unpubl.; McIlroy 1982, 1983) were conflicting due to the lack of control over a number of variables now known to influence the possum's susceptibility to 1080. This prompted a re-evaluation of the acute toxicity to captive possums of 1080 in different bait media (Henderson *et al*. 1999a), which controlled the following variables: colour-morph of possums (i.e. genotype), sex and age of possums, acclimatisation period, the delivery method (i.e. intubation versus bait delivery), the bioavailability of 1080 in different bait media, and the amount of food in the stomach. For groups of grey and dark (in a ratio of 1:2) acclimatised possums with continual access to normal diet, the LD_{95} of 1080 was 1.2 mg/kg in aqeuous solution, 3.6 mg/kg in cereal pellet baits, and 4.6 mg/kg in carrot, all values being significantly different from each other. Combining all bait media, susceptibility was influenced by colour morph, greys being more susceptible (2.9 mg/kg) than darks (4.1 mg/kg), and amount of food in the stomach, but not by sex or age.

It is important that the first bait encountered should contain a lethal dose as the latency of 1080 in possums is between 30 and 60 min (Chapter 5) and, moreover, because it is now considered desirable to use low sowing rates (Chapter 3). If a possum finds and eats a sublethal bait, it is likely to become inappetant before finding further baits, and on recovery it is highly likely to develop learned bait shyness (Chapter 6). Assessment of the variability of lethality of baits began with a study that estimated the number of randomly encountered baits, produced by different carrot cutters, that would be required to kill possums (Batcheler 1982). The prediction combined the measured frequency distributions for bait-weight and bait-1080 content and showed that for a range of carrot cutters, on average, between 2.4 and 3.8 random bait encounters would, if eaten, cause death in possums of 'median' susceptibility (i.e. killed by 1.5 mg/kg LD_{50} doses of 1080), and 3.2-5.7 encounters for 'tolerant' possums (i.e. 2.5 mg/kg LD_{95} doses). A similar exercise was conducted more recently for cereal pellet bait (Frampton *et al*. 1999) using data on bait-weight and bait-1080 content collected during three aerial 1080-operations conducted in forests at Puketi, Waipoua, and Titirangi in the North Island in the early 1990s. The study also incorporated variation in possum body weight from samples collected at each site and used a LD_{95} value of 2.5 mg/kg. The predictions were similar to those previously made for carrot: between 1.8 and 3.0 randomly encountered and consumed baits were required to achieve a 95% kill, and this was reduced to 1.7-2.8 by 'removing' baits weighing less than 4 g from the calculations. These two studies, however, both suffered from overestimation of the possum's susceptibility to 1080. The more precise LD_{95} values now available (see above) suggest that 95% kills would be achieved by random encounters with and consumption of 6.4-10.5 carrot baits, and 2.6-4.3 cereal pellet baits.

Combining the findings of these studies therefore demonstrates the failure of operational procedures to ensure that the first bait encountered by possums will be lethal. Several measures have been introduced to improve the production of baits of consistent size and lethality. Improved rotary screening devices were introduced in the 1990s to more effectively remove chaff (i.e. pieces weighing less than 2 g) from carrot bait, and the 1080 concentration used in most operations was increased from 0.08% to 0.15% wt:wt. Specifications, first developed for cereal pellet baits in 1987, were tightened with regard to bait weight and 1080 content, and increasingly these specifications (Appendix 3) together with routine laboratory analyses were used as Quality Assurance procedures. Specifications were also developed for carrot baits (Appendix 4) but as yet have not been formally adopted by control agencies, perhaps due to the substantial investment in new cutting and screening machinery that would be needed. In 1999, a larger type of cereal pellet (Animal Control Products, Wanganui) was introduced with a nominal mean weight of 12 g and containing 0.15% wt:wt 1080. Although formal assessments of the potential lethality of this bait type have not been undertaken, it is likely that the chances of sublethal bait encounter will have been greatly reduced compared with earlier 6-g pellets as fewer small baits are now produced.

Masking of 1080 was shown (Chapter 5) to be an essential procedure for ensuring that possums consume a lethal quantities of bait. As a result of the dissemination of this important finding through management-oriented publications (e.g. Morgan 1985) and presentations at technology transfer meetings, masking baits with 0.1%vol:wt cinnamon oil was introduced as standard procedure in the mid-1980s. More recent work (Henderson & Frampton 1999), however, has shown that the concentration of cinnamon oil in baits declines rapidly, stabilising at about 25% of the nominal concentration in carrot bait after only 2 days, and at about 40% of the nominal concentration in pellet baits after 8 weeks. The more rapid loss from carrot is most probably due to its application to the bait surface, while pellets contain the cinnamon (and 1080) as ingredients mixed throughout the baits. This led to recommended increases in cinnamon concentration (Henderson & Frampton 1999) to 0.3% vol:wt (i.e. a threefold increase) on carrot to ensure that sufficient masking (i.e. a minimum of 0.1% concentration) is retained for the field-life of carrot baits (which are used immediately following preparation). Similarly, a doubling of cinnamon content to 0.2% was recommended for pellet baits to provide adequate masking for the shelf-life (see below) of the product.

The effects of rain and freezing on bait lethality have also been partly assessed. Once rainfall exceeds 5 mm, 1080 is leached from cereal pellets rapidly such that about 80% of the toxicant is lost from RS5 pellets after 50 mm rain and after 100 mm of rain for No.7 pellets (Bowen *et al*. 1995; Booth *et al*. 1999; Morgan 1988). An operational specification for a maximum of 5 mm of rain was therefore suggested for use of cereal pellet baits. In contrast, 1080 content in carrot remained stable under 200 mm of rain (Bowen *et al*. 1995) and declines more as a result of microbial action. Thus, if it is necessary to return livestock to an an operational area before carrot bait has been biodegraded, samples baits should be assayed for 1080 content. The 1080 content of carrot baits subjected to freezing remained stable for at least 7 days after defrosting despite the release of a large volume of fluid (presumably due to cell lysis during defrosting) (Henderson & Frampton 1999).

7.2.2 Bait palatability

Adequate palatability of baits is of major importance in determining operational effectiveness because it can be influenced by a number of other factors (Fig. 7.1), which have been comprehensively assessed (Henderson & Frampton 1999). A standard method was used for assessing bait palatability in which caged possums were used to facilitate rapid progress, rather than conducting studies in the wild as described in Chapter 1. Palatability was measured by presenting 20 individually caged possums with a choice of the test bait and freshly made (i.e. < 2 months old) 'industry standard' RS5 cereal pellet (Animal Control Products, Wanganui) as a control. Each possum was presented with two trays containing 100 g of the two materials and consumption, corrected for weight changes in reference samples not available to possums, was measured after baits had been available to possums for 16 h overnight. Palatability was expressed as the weight of test bait eaten given as a percentage of the total consumption (i.e. test bait and control bait), and a value of 50% therefore indicates similar palatability of the two materials. Baits were calibrated for potential effectiveness in operational use by assessing the proportion of possums that ate sublethal quantities of toxic forms of the baits for which palatability values had already been established. This showed that most sublethally dosed possums were those that had fed sparingly on baits with palatability less than 30%, suggesting a minimum specification of 40% to allow a 'safety' margin.

Using the standard palatability method and the minimum specification for 40% palatability, Henderson & Frampton (1999) assessed the following major influences on bait palatability:

Bait type/variety: Nine different types of bait tested varied in palatability from 18 to 75%. Commonly used baits (cereal pellets, paste, gel, and carrot) all exceeded the 40% threshold. The palatability of seven varieties of carrot ranged from 56 to 82% and was influenced by the time that carrots had been grown. Chantenay carrots were the most palatable and there was an overall trend of younger (3 months) carrots being more palatable than older carrots (4 and 5 months). For Chantenay carrots, the growth period and mean size both affected palatability leading to specifications for harvesting within 6 months or before they reach a weight of 200 g. Carrot palatability was also found to be unaffected by the presence of soil residues (i.e. unwashed). Frozen 1080 carrot baits showed a reduction in palatability once defrosted from 74 to 54% over seven days.

Moisture content: The stability of cereal pellets during storage was shown to be influenced by moisture content since higher levels of moisture promoted growth of mould and bacteria resulting in reduced palatability. However, RS5 pellets containing the standard 12% moisture and preservative showed no increase in mould counts over 4 months and remained palatable for this time.

Bait storage: Five bait types were tested over a 12-month period of storage at room temperature and all showed a decline in palatability. Using the 40% palatability minimum specification, shelf-life was 6 months for RS5 pellets and 3 months for No. 7 pellets. Carrot bait, stored outdoors in autumn after preparation, retained high palatabilty (around 78%) for one week, after which palatability declined but remained above 65% for a month.

Bait hardness: Hardness of baits was measured using a 'Penetrometer' to deliver pressure via a 2-mm-diameter probe to the side of baits until breakage occurred. RS5 pellets that were very hard (i.e. resisted more than 12 kg pressure) had a lower palatability of 22%, while baits that were too soft (i.e. resisted less than 5 kg pressure) crumbled easily increasing the risk of sublethally poisoning possums. A specification of 5-12 kg pressure resistance using a 2-mm Penetrometer probe was therefore recommended.

Rain: RS5 pellets that were dampened showed increased palatability (corrected for added moisture) after one day. The increase in palatability was correlated with the amount of moisture added such that saturated baits (50% by weight added moisture) showed the greatest increase from 52 to 73% palatability. However, palatability of damp baits began to decline after 2 days but still exceeded the 40% threshhold after 8 days. Since most (>90%) possums eat bait within 2 days of aerial application (Chapter 2), this suggests that operational effectiveness is unlikely to be reduced by showers making baits unpalatable.

The studies described above relating to bait lethality and palatability have yielded considerable new information that can be used to help prevent poor-quality baits being used operationally, and the key recommendations have been incorporated in the updated bait specifications made available to pest managers and bait producers (Appendices 3 and 4).

7.3 Bait delivery

The importance of complete coverage of target areas by aircraft was demonstrated in Chapter 3. Even small gaps in baiting coverage are likely to enable possums to survive since home ranges as small as 0.3 ha (e.g. 300 x 100 m) or less have been reported in four independent studies of possums in New Zealand forests (summarised in Cowan & Clout 2000). Effective aerial bait delivery can be achieved by controlling the sowing rate and uniformity of sowing baits, and effectiveness can be assessed by measuring dispersion of bait on the ground (Fig. 7.1).

7.3.1 Sowing rate

Sowing rate can be predicted if the following parameters are known: output rate of the distribution equipment; flying speed of the aircraft; and swath width achieved.

$$\text{Sowing rate (kg/ha)} = \frac{\text{Output rate (kg/min)}}{\text{Rate of area coverage(ha/min)}}$$

If flying speed is measured in km/h:

$$\text{Sowing rate (kg/km of swath)} = \frac{\text{Output rate (kg/min) x 60}}{\text{Flying speed (km/h) x swath width (m)}}$$

Calculation of sowing rate in the most convenient and useful units is then achieved by (1) converting into hectares covered rather than kilometres of swath:

$$\text{Sowing rate (kg/ha)} = \frac{\text{Output rate (kg/min) x 60 x 10 000}}{\text{Flying speed (km/h) x 1000 x swath width (m)}}$$

$$= \frac{\text{Output rate (kg/min) x 600}}{\text{Flying speed (km/h) x swath width (m)}}$$

and (2) by converting flying speed into 'knots' (1 knot = 0.54 km/h), as universally used in aircraft:

$$\text{Sowing rate (kg/ha)} = \frac{\text{Output rate (kg/min) x 324}}{\text{Flying speed (knots) x swath width (m).}}$$

This formula can be used to calibrate aircraft sowing equipment. For example, helicopter sowing buckets can be calibrated to achieve specified sowing rates following the protocol (Appendix 5) that I prepared for the field trials described in Chapter 3.

7.3.2 Uniformity of sowing

To achieve uniform coverage of the target area, it is essential that: (1) aircraft distribute baits along flight paths that are correctly spaced and parallel, and (2) bait distribution from sowing equipment occurs uniformly during flight.

Considerable advancement towards these aims has occurred within the aviation industry since 1990. Both fixed-wing aircraft and helicopters can now be fitted with real-time differential GPS-based guidance units that can be calibrated to give a positional accuracy of a few metres. In practice, pilots generally prefer to use a slightly lower level of accuracy of around ±10 m to provide a more 'stable' guidance signal during flight. Maps of flight paths can be downloaded at appropriate resolutions for overlaying on GIS-based maps of the target area. Precise and rapid identification of gaps in coverage is therefore feasible using GIS software to identify the coordinates of gaps. A list of such coordinates can then be assembled for entry into the aircraft's GPS unit for establishing the optimal flight paths required for treatment of the gaps. Indication of the approach distance to such gaps during the 'reflight' is given via the GPS display to permit precise targeting of gaps.

The actual distribution of baits during flight is recorded, most simply, by the pilot observing bait flow and activating the output control switch (for opening and closing sowing buckets or hoppers) for logging the event on the flight-path recording. While this method ensures precise data-logging, it does not reveal instances where no bait was distributed due to blockages. Some pilots therefore manually log bait application based only on their direct observation of bait flowing from the sowing device. This method is not suitable for fixed-wing aircraft, as the backward flow of baits cannot be easily seen by a pilot, nor is it suitable for application of baits at rates lower than about 3 kg/ha as it becomes increasingly difficult to confirm bait-flow by sight at low rates. Automatic recording of bait flow is the most desirable means of ensuring accuracy. However, several types of sensor (using light, conductance, and weight) have been tested in conjunction with aircraft sowing buckets and, to date, none have proved reliable due to their sensitivity to vibration, dust, and impact with baits. As described earlier (section 3.6.1), a system is presently under development that aims to link sensor-detection of interruptions to bait flow with a video recording (for verification) and GPS position data (to enable programming of flightpaths for treatment of gaps). Further desirable improvements include automatic regulation of the application rate of baits for changes in airspeed due to winds, and changes in the rate of area-coverage due to changes in gradient.

7.3.3 Bait dispersion on the ground

With the current state of aerial-bait-application technology, clearly there is potential for gaps in coverage and irregular distribution of baits to occur. Gaps are likely to lead to failure of some possums to encounter baits, whereas baits that are too sparsely distributed could result in sublethal poisoning if some possums encounter only a small quantity of sublethal bait in the 30-45 minutes before they become inappetant. In addition to the logging of flight paths and bait sowing, it is therefore desirable to assess the actual dispersion of baits on the ground after aerial application, particularly where new machinery is being used. The methodology I used in the aerial sowing trials described in Chapter 3 has since been simplified for quality assurance assessments of dispersion of baits on the ground (Appendix 6). This procedure can be used to estimate both the density of baits on the ground (e.g. Table 3.4) and the proportion of the block treated (e.g. Table 3.5). More sophisticated analyses of the data make use of the negative binomial distribution for describing conformity with a random dispersion pattern, and the parameter '*k*' can be used as an index of 'clumping' (e.g. Table 3.3). The surveys required for such assessments also provide the opportunity to estimate the degree of bait breakage resulting from bait handling, sowing, and impact with the forest canopy (Appendix 7). If baits are not hard enough, it is likely that bait breakage will occur, increasing the risks of sublethally poisoning possums and mortalities of birds that are inclined to feed on small particles. While the maximum specification for bait hardness has been established in relation to bait palatability, the minimum specification has been set in relation to the likelihood of baits to fragment. However, the minimum specification has not been confirmed against measured fragmentation of baits used operationally.

7.3.4 Prefeeding

The provision of non-toxic bait to reduce subsequent rejection of toxic bait (i.e. prefeeding) has been assessed experimentally and operationally (Henderson & Frampton 1999). The amounts of 1080 cereal pellet bait eaten by penned possums more than doubled following exposure to non-toxic pellets for 3 nights compared with possums that were not prefed, and survival due to consumption of sublethal baits was reduced. For aerial control operations using 0.08% 1080 carrot bait, the mean kill in non-prefed operations (n = 16) was 77.3% which was significantly greater than the mean kill of 91.3% for operations that were prefed. Corresponding kills for operations using 0.15% 1080 carrot were 84.0% (n = 4) and 99.3% (n = 1). In Wellington Regional Council operations using pellet baits reported elsewhere (Animal Control Products 2000), reductions of 94.0-100% (n = 4) were achieved in pellet operations using prefeed, while one operation without prefeeding gave a lower kill of 87.7%. However, of six recent Department of Conservation operations (reports sourced from A. Fairweather), three with prefeeding achieved kills of 88.1 to >98% and three without prefeeding achieved kills of 98-100%. (The optimal delay between prefeeding and applying 1080 bait, based on an assessment of 13 operations, is between 9 and 14 days (Animal Control Products 2002)). Clearly there is a need to establish the cost-effectiveness of prefeeding by a comprehensive analysis of recent operational data, similar to that conducted by Brown & Arulchelvam (1995) before prefeeding became common practice. This analysis should also incorporate population growth modelling to predict the relative long-term benefits of aerial control with and without prefeeding.

Presently prefeed baits are usually presented without dye, distinguishing them from toxic baits which are dyed green, a colour known to be aversive to many bird species (e.g.

Caithness & Williams 1971, and further discussed in section 8.3.3). To avoid the possibility that non-dyed baits may be eaten by birds leading to their subsequent feeding on toxic baits, it may be advisable to simply prepare all baits, whether toxic or not, with green dye. As an additional safeguard, chemicals that are repellent to non-target species but not possums could be included in baits (e.g. Day *et al*. 2003).

7.4 Conclusions

This research review shows that most of the factors that influence the quality of present baits and their optimal aerial delivery for controlling possums have now been well researched. The research findings have been used to prepare quality specifications for baits that can be used as the basis for supply contracts, and methods have been developed for assessing the quality of baits in relation to the specifications. The research methods used in the study of bait delivery have been adapted to form protocols suitable for routine use by operational managers in checking sowing rates and coverage. Research on bait delivery (Chapter 3) helped promote the use and development of navigational guidance systems and improved sowing buckets. Collectively, the specifications, protocols, and improved hardware provide managers with 'tools' for achieving better control of the physical and chemical characteristics of baits and bait delivery, and consequently, improved operational success. The variables that are not controllable, which still present a significant threat to operational success, are climatic factors. Other researchers have partly determined the influence of the major climatic variables, including the effect of rain on bait palatability/lethality (section 7.2.2), and the influence of temperature on bait lethality (section 4.4.3). However, for optimal scheduling of control operations in relation to weather forecasts, information is needed on the effect of climate (especially rain and wind) on possums' feeding behaviour since harsh weather may increase the likelihood of sublethal dosing.

There is also a need for development of new bait types and processing methods since the research presented shows that current baits are deficient in some respects. While the specification for each bait to carry a lethal dose was recognised long ago (Peters 1975), the research summarised here (section 7.2.1) indicates that this has not yet been fully achieved. However, subsequent changes in manufacturing equipment at the main source of supply of cereal pellet baits have led to baits of more regular size and, hence, lethality (Animal Control Products 2000). It was also evident to me during a field visit to three operations during winter 2002 that the operational managers (responsible for the majority of aerial operations being conducted in the North Island) had devised improved systems for both the production of more uniform carrot baits and improved monitoring of the application of 1080 to the bait. It therefore appears that the need for uniform, lethal baits is well recognised and measures are being introduced to achieve this aim. However, alternatives to the present extrusion process for forming pellet baits should be explored such as moulding or pressing of materials into baits of exact size. For pellet baits, 1080 could be introduced into the baits in precise doses during such processing. Presently I am collaborating with a manufacturer to develop pellet baits containing precision-made microtablets containing specified doses of 1080. These baits are designed to avoid sublethal dosing and subsequent bait-shyness: furthermore, possums that only nibble the bait would be unlikely to ingest any 1080 and this ‘prefeeding’ would be expected to result subsequently in consumption of a larger (lethal) quantity of bait.

Another reason for continued bait development is the need for baits of longer field-life. This results from the change in operational strategy from ‘initial’ operations against medium- to high-density populations towards ‘maintenance’ operations against low to very low density populations. Where possums are distributed sparsely, there is a need for baits to remain palatable and lethal for longer than present baits, particularly under the lower sowing rates now being adopted. Wax-coated pellet baits are available that extend field-life when used in ground-based operations (i.e. placed in bait stations) (Morgan 2003), but it is likely that they would be less suitable for aerial application because damage to the coating results in rapid breakdown of the bait and, furthermore, it is likely that baits would tend to clump in sowing equipment particularly during warm weather.

High standards of bait quality and delivery are essential for operational success. However, this must form part of a ‘Total Quality Management’ approach to sustained possum control that embraces planning, training, certification, performance monitoring, population modelling, technology transfer and research-by-management (Morgan 1995). By removing uncertainty, operational results are apparently becoming more predictable (although analysis is needed, as suggested above) enabling better definition of the technical sustainability of aerial control, but this must also be integrated with the ecological, economic and socio-political dimensions of sustainability, as discussed in the following chapter.

Chapter 8. Future Use of Aerial 1080 Poisoning in Strategies for Sustained Control of Possum Populations

8.1 Introduction

Aerial 1080 poisoning of possum populations was introduced in the late 1960s supported by very limited technical information. The research I have described in previous chapters has greatly improved the basis for using the method. In the future, however, its continued use will be determined not only by technical proficiency, but also by a number of other potential and actual constraints. In this chapter, therefore, I firstly consider the need for use of aerial control operations before discussing the wider aspects that may limit its use. Secondly, because the research was designed at the outset to solve the problem: "Why do possums survive aerial 1080 control operations?" I summarise the main management implications of the research and discuss the uptake of the research findings by managers. Thirdly, I summarise those areas of inadequate knowledge, identified in earlier chapters, where there is a need for further research to provide further advice to managers.

8.2 Future need for aerial 1080 poisoning operations

Information obtained recently indicates that, in 2003, possum populations were subjected to control (by all methods) on a total area of around 7.8 million ha through a combination of AHB Tb-control operations (6.8 million ha - N. Hancox, 1 July 2003, pers. comm.) and Department of Conservation estate management (1 million ha – P. Lawless, 29 July 2003, pers. comm.). The extent of possum control will, however, substantially increase under the strategies adopted by these two main management agencies.

The Animal Health Board (AHB 2001) has expressed confidence in being able to extrapolate past success in controlling Tb, and is now committed to a policy of eradicating the disease rather than controlling it. The first step in achieving eradication is achieving 'provisional freedom'. (By international agreement, this means achieving an incidence of less than 0.2% of cattle and deer herds being infected with the disease for a period of three years). Its present Tb management strategy (AHB 2001) aims to achieve year one of provisional freedom from Tb for New Zealand's national livestock herds by 2012. To contain known infected areas and to provide adequate buffer zones, the AHB strategy predicts this can be achieved if there is an extension of the area in which possum control is sustained to 8.4 million ha, by 2005. (This area includes some areas where ferret populations will also be controlled, but not the comparatively small area in which ferrets alone will be controlled.) The Department of Conservation also expects to increase the area of conservation estate over which possum populations are controlled (A Fairweather, DOC, 12 December 2002, pers. comm.).

Aerial 1080 poisoning is being conducted on approximately 1 million ha annually by the Animal Health Board (N. Hancox, 1 July 2003, pers. comm.) and on 130 000 ha annually by DOC ('Assignment', TVNZ, 25 April 2002), which is about 15% of the total area over which possums are controlled (note: the total includes substantial areas of farmland which are not treated thus leading to underestimation of the proportion treated by aerial 1080 baiting). Most possum control is presently implemented using ground-based methods of control. However, it is likely that there will be a growing demand for the use of aerial 1080 poisoning for two reasons. Firstly, the supply of appropriately skilled contractors and agency staff to plan and conduct ground-based control is limited and unlikely to grow quickly enough to meet the demand for an increase in the amount of control until 2005. Control agencies are therefore likely to rely more heavily than in the past on aerial 1080 poisoning to meet this demand. Secondly, ground-based control operations take much longer to complete compared with aerial operations. For example, a 20 000-ha 'initial' (i.e. as opposed to 'maintenance') aerial operation in the Hauhangaroa Range in 2000 that resulted in a residual-population trap catch of 0.2% from 2550 monitoring trap-nights was completed in 6 weeks using prefed 12-g No.7 ACP pellet bait (B. Martin, horizons.mw, 21 June 2002, pers. comm.). By comparison, in a 8500-ha ground-based initial operation at Ngamatea on the Central Plateau in 2001, six contracted personnel (Central Districts Pest Control) also reduced a possum population to a very low density (i.e. <0.4% trap catch from 1650 trap-nights) in 3 months (M. Brenstrum, Central Districts Pest Control, 13 July 2002, pers. comm.) and this was considered to have been a rapid ground-based operation. Additionally, the longer time required for ground-control operations reduces the availability of ground-control personnel to undertake further work. Many contracting companies developed out of the possum fur-retrieval industry in which trapping and cyanide were used as the main tools (as they ensure that fur can be recovered). However, faced with the growing pressure to complete operations more quickly, several private contracting companies are now supplementing ground-based methods with the use of aerial 1080 poisoning operations, particularly in remote, rugged terrain. Since it is expected that there will be an increasing demand from possum managers to use aerial 1080 poisoning in the future, it is necessary to consider the possible reasons why this control method could become unsustainable.

In a broad sense, future use of 1080 may be partly determined by the development of biological control methods. These were initially viewed by some as a possible replacement for the use of conventional control methods, and Williams (1994) suggested the phased withdrawal of 1080 as a means of preserving its short-medium term use until new methods are available. Considerable progress has been made in developing methods based on the use of pathogens and parasites, interference with lactation, immunocontraception and other physiological disruptions (Royal Society of New Zealand 1998). However, as concluded by Cowan (2000) in a review of the topic, it is now more likely that biocontrol methods will be used to complement conventional control rather than replace them. Moreover, this will be dependent not only on the successful completion of research to understand and exploit biological mechanisms, but wider research and discussion of the ethical, social and political implications of this new technology. Biotechnology may therefore modify the extent and manner of 1080-usage in future. Data from recent studies on the likely effectiveness of biocontrol agents (e.g. Ramsey 1999) should be used to start the modelling of new control strategies that integrate both conventional and novel control methods. In addition to this possible broad influence on future control methodology, there are a number of factors presently influencing the continued use of 1080, especially by aerial delivery.

8.3 Factors influencing the sustainable use of aerial 1080 poisoning

If aerial 1080 poisoning is to remain a cornerstone method of controlling possums, it is important to identify factors that have been demonstrated, or suggested, as reasons why it could become ineffective or unsustainable in future. I have categorised these factors as being of a technological, economic, environmental, or social nature.

8.3.1 Technological factors

The research described in this thesis has followed a logically structured problem analysis (Fig. 1.1) to identify the reasons why possums may survive aerial poisoning operations and to find appropriate ways of reducing survival. Although the technology adopted has resulted in an increase in average success of operations from 70% in the 1970s to around 95% at present, at least one potential weakness in the technology remains: that is, the possibility of physiological resistance to 1080 developing by the selection pressure of repeated poisoning, in the same way that anticoagulant-resistance has developed in high proportions of rat and mouse populations to anticoagulants for decades in Europe (Pelz *et al*. 1995, MacNicoll *et al.* 2001).

Howard *et al*. (1973) reported the experimental induction of a 75% increase in tolerance to 1080 in rats after only five generations of selective breeding, and it was suggested that this could threaten the sustainability of 1080-use for rat control. While Wheeler & Hart (1979) previously found no empirical evidence for increased physiological resistance in rabbits after more than 20 years of regular 1080 poisoning operations, a recent evaluation of this possibility found that some rabbit populations showed a significant increase in tolerance (i.e. approximate doubling of LD_{50} values) over a 25-year period (Twigg *et al*. 2002). Potentially, selection for resistance in possums could occur since 1080 may be used repeatedly in some areas. For example, 1080 paste baits are sometimes applied on farmland in the period between successive aerial 1080 operations conducted in adjacent forest. Possum populations in the vicinity of the farmland/forest interface (the most critical habitat for control of bovine Tb) may therefore be repeatedly exposed. Experimental comparisons of the lethality of 1080 towards possums from these areas compared with possums from non-1080-treated areas are therefore required to determine whether this practice is sustainable. At the operational level, the anticipated move towards aerial application of precision-made baits at very low rates is more likely to reveal an induced physiological resistance to 1080 than present strategies that ensure that most possums consume multiple doses of poison. Possums with a marginally greater tolerance towards 1080 would have a survival advantage under such circumstances. The effect of a genetically based physiological resistance on the effectiveness of control would be the same as the effect of inherited behavioural resistance (i.e. innate bait-shyness), which has been modelled by Hickling (1995). Assuming that genetically resistant animals comprised 5% of a population and were only half as likely to succumb as non-shy animals, he predicted that annual control would become ineffective within a decade. While it is highly unlikely that 5% of possums in a population would simultaneously express a similar random mutation conferring 1080-resistance, such mutation has only to occur once for it to eventually become established in a population exposed to 1080 periodically. Further modelling is required to more precisely determine the likely impact of a resistance mutation over time. If resistance is suspected and confirmed by subsequent controlled experiments (as above), it would be necessary to use alternative control methods (without 1080) or higher doses of 1080. The possibility should also be examined that bait-shyness behaviour may be heritable, resulting in reduced operational effectiveness. However, this appears unlikely as four of five offspring of bait-shy, captive female possums were killed after consuming 1080 baits on initial exposure (Morgan & Milne 1997).

8.3.2 Economic factors

Possum control is economically sustainable if the benefits gained are outweighed by the costs incurred. It is impossible to separate the benefits of aerial and ground operations because they are usually both applied to a particular situation during the term over which benefit is assessed. Earlier research suggested that aerial and ground control were of similar cost-efficiency (Morgan & Warburton 1987) and, although further developments in both techniques have improved efficiencies, both methods can presently be expected to meet a target of less than 5% RTC[1] at a cost of \$12-20 per hectare in most cases. The economic sustainability of possum control in total will therefore be considered as a reflection of the likely sustainability of aerial 1080 poisoning.

The benefits of possum control comprise: (1) the agricultural (including forestry and horticulture) output maintained as a result of possum control, and (2) preservation of conservation values, for which estimation in other contexts has been attempted using 'contingent valuation' (e.g. Holmes & Kramer 1996). No data are available on the economic value of these benefits gained from possum control. Although agricultural losses were assessed as \$21 million per annum in the early 1990s (Bertram 1999), this represents the value of losses tolerated under a certain level of possum control. For the purposes of cost–benefit analysis of possum control, data are needed on the value of the additional agricultural losses that would occur if possum control were not undertaken. Even where some data are available on non-economic benefits of control (e.g. reduction of Tb infection levels in cattle), extrapolation to predict required levels of control for particular benefit goals is unreliable because the behaviour of certain parameters (e.g. infection processes) cannot be assumed to be constant under changing possum population density (Hickling 2001).

Similarly no data are available on the economic value of protecting native flora and fauna from possum damage. Bertram (1999) describes four methods (i.e. contingent valuation, hedonic pricing, travel-cost valuation, and production-function valuation) by which the public's 'willingness to pay' could be used to determine this value. Public opinion must be

---

[1] Residual Trap Catch, i.e. the percentage of traps that catch possums following the methods given in NPCA (2002)

assessed through extensive questionnaires to provide the basic data for such methodologies. As an alternative, Bertram argues that government spending on pest control since the 1940s is a good indicator of the value of pest control since sufficient debate and turnover of decision makers would occur over such a long period to ensure that New Zealanders' willingness to pay has been revealed. However, this approach results in a tautological argument if applied to the cost–benefit analysis of possum control because independent estimates of both cost and benefit are needed rather than assuming they are equal.

Clearly, there is presently a limited ability to justify possum control on a marginal cost–benefit basis. Rather it is justified largely on the basis of perceived risk to agricultural exports (see section 1.2.4) and on the negative impacts on non-market conservation values. Nevertheless, alternatives to cost–benefit analysis can be used to assess the economic sustainability of possum control, as suggested by Choquenot *et al*. (2001). 'Benefit-maximisation' can be used to compare the long-term benefits (e.g. improvement in forest canopy condition) of different control strategies where control budgets are fixed. Alternatively, where a predetermined level of benefit is specified (e.g. maintenance of a stable population of kokako), 'cost-minimisation' can be used to identify the lowest cost of achieving this under different management strategies. While these methods do not provide a direct comparison of cost and benefit, they do enable managers to rationally design optimal long-term control strategies. For example, using the cost-minimisation method as part of a wider decision support system, Choquenot & Parkes (2000) identified the best strategy for reducing and sustaining possum populations at densities below 1 possum/ha, a density low enough to prevent the recycling of Tb. Aerial 1080 baiting was predicted to achieve this within 10 years using maintenance operations at 5-year intervals, while ground hunting required 30 years at the same interval. Comparisons of the longest maintenance intervals required to permanently suppress the population also favoured aerial baiting (7 years) over ground control (5 years). These predictions may be conservative, however, as independent modelling by Veltman & Pinder (2001) concluded that local eradication of possums would be possible in a period of 30 years using aerial 1080 baiting at 6-yearly intervals.

Decision support systems that have been developed to help pest managers make better decisions include: (1) 'EpiMAN (Tb)' which integrates a number of computer-based tools that predict where possum control will be most effective for Tb management (MacKenzie 1997), and (2) 'Optimise', which also uses computer-based tools to simulate and compare the cost-effectiveness of alternative control strategies (McGlinchy 1996). A system presently under development includes bait shyness as a factor in modelling the costs and benefits of different frequencies of control aimed at protecting forest canopies. The development is part of an 'adaptive management' project in which possum populations and forest canopy are being monitored to provide a range of values that will enable refinement of control strategy for either cost-minimisation or benefit-maximisation (Parkes *et al.* 2003).

Further efficiency in aerial control of possum populations may be possible through integrating the management of several pest species where they coexist (Morgan 1993). While this occurs informally at present, a more explicit statement of multi-species control objectives is needed to enable transparent planning and assessment of the benefits gained. As well as additional economic benefits, there may be additional ecological benefit in muti-species aerial baiting. For example, if a bait suitable for aerial control of stoats was available, this could be distributed during aerial control operations against possums to enable simultaneous control of stoats, possums and rats. This would aim to prevent the increase in stoat populations that normally occurs when rats are removed, and hence avoid stoats 'prey-switching' from rats to native birds as reported by Murphy & Bradfield (1992).

8.3.3 Environmental factors

Sustainable use of aerial 1080 poisoning requires that any unwanted environmental effects are considered acceptable in relation to the benefits gained. Many research studies have been conducted in New Zealand on the environmental effects of 1080 as used in possum control because 1080 is used more widely in this country than elsewhere. These studies have been reviewed in Eason (2002) and Morgan & Eason (2003) on which the following summary is based, supplemented by findings from other recent studies (for which citations are given).

Water and soil contamination. Monitoring of water quality at operational sites over a 10-year period showed no 1080 traces in locally reticulated water supplies, and transient trace amounts (i.e. <5 ppb) of 1080 in about 5% of samples collected from streams within target zones. Laboratory studies showed rapid breakdown of 1080 by aquatic plants and microorgansims, but slower breakdown (i.e. 1-2 weeks) at <7°C. Despite the experimental demonstration of biodegradation of 1080 in stream water, in fast-running streams dilution of the poison was considered more important in reducing the presence of 1080 to toxicologically insignificant concentrations. Also, 1080 leached from baits is also denatured rapidly by soil bacteria.

Invertebrates. Field surveys detected no impact on populations of weta in Waipoua Forest, a range of invertebrate species on Rangitoto Island, predatory insects in Mapara Reserve, or ground-dwelling invertebrates in Puketi Forest and Titirangi Reserve. Observations of the numbers of species and number of individual invertebrates found feeding on 1080 baits has led to the prediction that vertebrate pest control operations are unlikely to have any long-term deleterious impacts on invertebrate populations.

Birds. Current evidence suggests that populations of common bird species are not adversely affected. Non-target effects of 1080 used for possum control have been studied extensively during the last 20-30 years. Most dead birds were found after large-scale control operations and trials using non-dyed, raspberry-lured, unscreened carrot bait that had a high percentage of small fragments or 'chaff'. Thus earlier bird deaths were attributed to primary poisoning through consumption of poorly prepared baits. Fewer and fewer species of birds have been reported dead after 1080 poisoning operations since 1977, but the loss of any individual birds is undesirable. Most birds found dead were introduced species (blackbird (*Turdus merula*) and chaffinch (*Fringilla coelebs*)), but some native birds were also killed. These losses were usually small, in population terms, for any of the more common bird species in the 35 operations where bird populations were monitored both before and after poisoning. In one case, a significant reduction was reported in a population of native robins (*Petroica australis*) after possum control using prefed carrot bait, but this was followed by a population increase, suggesting that robin populations benefit in the longer term. Powlesland *et al*. (2000) found that populations of North Island tomtits (*Petroica macrocephala*) were reduced in two carrot bait operations. However, Westbrook *et al*. (2003) concluded that such mortality is likely to be associated with higher sowing rates (10-15 kg/ha) of the past, and since cereal baits sown at 3-5 kg/ha in two operations had no impact, they suggest that further monitoring of tomtits should be conducted during operations that use carrot bait at similarly low rates of 3-5 kg/ha. Less common native bird species (e.g. brown kiwi (*Apteryx australis*) and kokako (*Callaeas cinerea*)), however, have been less frequently monitored, at least for some bait types. However, radio-tracking has shown 100% survival of 21 kaka (*Nestor meridionalis*), 19 blue ducks (*Hymenolaimus malacorhynchos*), and 24 North Island brown kiwi following aerial 1080 baiting. The risk of secondary poisoning effects on bird populations has been assessed showing that some invertebrates do eat baits, but 1080 persistence in invertebrates is short-lived and the risk to insectivorous birds or other predators is therefore also confined to a short period after sowing baits for possum control. Reductions in bird deaths since 1978 can be attributed to the screening of carrot baits to remove small fragments (which are likely to be eaten by birds and insects), the banning of raspberry lure (attractive to some birds), the use of cinnamon oil as a deterrent, the reduced rates of bait application, and the increased use of cereal-based baits. Bait specifications (Appendices 3 and 4) now minimise the amount of fragments in bait consignments, which in turn minimises the effects on populations of non-target species. While populations of common bird species are generally unaffected by aerial poisoning operations, a wide range of individual birds have been killed. Research with introduced birds showed that colouring baits green was an effective means of deterring birds (Caithness & Williams 1971) but limited studies with native birds have yielded more equivocal data. Although weka (*Gallirallus australis*) were deterred by green baits, robin were more effectively deterred from feeding on blue or brown food (Hartley 1999, Hartley et al. 2000) suggesting that further studies are needed to determine the optimum colour of baits for deterring birds.

Mammals. While 1080 is eliminated from living animals rapidly compared with anticoagulant poisons, it can persist in carcasses for many months where it breaks down more slowly, particularly in cold weather, posing an important risk to dogs. Dogs are about 20 times more susceptible to 1080 than possums and, moreover, display repeated convulsive fits over a period of 4-6 hrs before death. Prevention by restraining dogs from wandering is the only sure protection. Although simple emetic treatment (using solutions of salt or washing soda – Eason &Wickstrom 2001) is available and effective if administered within an hour of baits being eaten, dogs may not return from wandering within this period. Predators, such as stoats, ferrets, cats, rats and pigs, may also be killed through secondary poisoning if sufficient 1080 remains and is ingested. Deer and pigs are perceived as both valuable hunting resources and troublesome pests, depending on the perspective from which they are viewed. Although both species are controlled by the Department of Conservation in certain areas, they are also sometimes affected as a by-kill of possum control operations. By-kill rates of deer for aerial operations using cereal bait range from 5 to 54%, while by-kills exceeding 90% have been recorded where carrot bait was used. However, recent research on the use of a deer repellent (which is not repellent to possums) indicates that a solution may soon be available (G. Nugent, 9 Feb 2004, pers.comm.). Native short-tailed bats (*Mystacine tuberculata*) (n = 269) were observed in captivity after an aerial 1080 operation and none showed any signs of 1080-poisoning, but additional studies are required before safety towards this species can be generalised (Lloyd & McQueen 2002).

Human health. Humans could be exposed to 1080 through several possible routes: drinking water, contaminated meat or milk, and dust or vapour from baits. Exposure to contaminated drinking water is very unlikely (see above): even at the highest levels of contamination found, that is 4 ppb (G. Wright, 20 March 2003, pers. comm..), a 90-kg person would need to drink 45 000 litres of water at one time to ingest an LD_{50} dose of 2.0 mg/kg (i.e. the lower limit of a range given by Chenoweth (1949)). Despite strict precautions, it is possible that livestock may encounter and eat sublethal quantities of 1080 baits during possum control operations, thus raising the possibility that contaminated meat or milk may be consumed by humans. Absorption, metabolism, and excretion studies of laboratory animals since the 1950s have shown that sublethal amounts of 1080 are rapidly absorbed and distributed through the soft tissues and organs, from where it is excreted both unchanged and as a range of non-toxic metabolites. This contrasts with the action of commonly used anticoagulant rodenticides, such as brodifacoum, which are extremely persistent. The highest concentrations occur in the blood, with moderate levels in the muscle and kidneys, and the lowest concentration in the liver. Prolonged persistence of 1080 in animals after sublethal exposure is unlikely, as 1080 was readily absorbed and excreted in studies with larger animals such as rabbits, goats, possums, and sheep. Milk contamination peaked at 4 h after an LD_{20} dose in sheep (selected as a conservative model for cows), but the concentration was very low, and it was estimated that a person would have to drink 120 times their body weight to receive an LD_{50} dose. The significance of the comparatively rapid metabolism and excretion is that 1080 is unlikely to bioaccumulate in the food chain. All traces of the toxin are likely to be eliminated within 1 week. If recommended practices are followed in possum control operations, 1080 is unlikely to be present in meat or milk for human consumption. Where any contact of livestock (farm animals or animals intended for slaughter) with 1080 is suspected, an adequate margin of safety should be achieved by imposing a minimum withholding period of 5 days. Regulatory toxicology studies, conducted to assess human health hazards, indicate that prolonged exposure of rats to sublethal doses of 1080 may lead to malformations in developing embryos, but no evidence of mutagenic effects was detected. This work has underpinned the maximum exposure levels (0.05 mg 1080/m^3 air) and 'biological exposure index' (15 µg 1080/L urine) recently set by the Occupational Safety and Health Service (Department of Labour 2002b). While these levels of exposure are unlikely to be experienced through contamination of drinking water, meat and milk, workers in the bait manufacturing industry could become exposed through contaminated air if adequate precautions were not taken. Standard safety practices have been enhanced to minimise this risk (Department of Labour 2002a).

Following the convention that risk is a product of the hazard presented and the likelihood of being exposed to the hazard, I have subjectively ranked the main known risks presented by aerial 1080 poisoning (Table 8.1). Considerable research on the effects of 1080 is being conducted and it is possible that other risks may be identified.

Table 8.1 Assessment and ranking of the main environmental risks posed by aerial application of 1080 baits in possum control

Priority of risks	Hazard	Likelihood of exposure
1. Secondary poisoning of dogs	Possum carcasses	Possible if dogs are not restrained and carcasses are slow to biodegrade
2. Primary poisoning of deer	Baits	Dependent on the application rate of baits. Likely to be reduced by low application rates and use of a deer repellent.
3. Deaths of individual birds	Small bait fragments	Can be minimised by use of pellet baits, removal of bait fragments, and low application rates.
4. Chronic sub-lethal effects in industry workers	Dust and vapour	Minimised by use of 'safe practice' procedures.

Environmental benefits. While the impact of possums on vegetation is well researched, studies on the response of vegetation to possum control are limited, and are summarised in Norton (2000). At Waipoua Forest, aerial poisoning in 1990 achieved 87% mortality and arrested the decline in forest canopy condition, but during the 4-year term of the study, no general improvement in forest health was detected. Possums were eradicated from Kapiti Island in 1986 after 6 years of intensive control using both ground-based and aerial methods. While damage was extensive beforehand, control led to rapid improvements in the health of key forest species. Less obvious benefits accrued from aerial- and ground-control in the Otira-Deception Valleys in Westland during 1988-96. Overall the forest canopy of southern rata (*Meterosideros umbellata*) and kamahi (*Weinmannia racemosa*) appeared to improve in condition and there was decreased damage to understorey plants such as fuschia (*Fuschia excorticata*) and pate (*Schefflera digitata*), but trends were not confirmed statistically. Several studies have shown rapid regrowth of mistletoe species (*Peraxilla terapetala* and *Tupeia antarctica*) after possum control. Additionally, aerial control on Rangitoto Island in

1992 killed 90% of possums and led to such an improvement in the health of the main food source for honeybees, pohutakawa (*Meterosideros excelsa*), that honey production increased nearly sevenfold from 2.5 tonnes to 17 tonnes the following year (Butcher 2000). Norton (2000) attributed the reasons for the paucity of data to the relative recency of widespread possum control, methodological difficulties in assessing vegetation response, confounding effects of other pest species, low inclination of conservation managers to formally publish results, and the lag between control and measurable responses.

Studies of the benefit of possum control to native wildlife were reviewed by Veltman (2000) who, like Norton, found that few reliable studies had been conducted. Those reported all followed periods of ground-based possum control and included bird counts on Kapiti Island, snail counts at Charming Creek (North Westland) and elsewhere, insect browsing indices at Whirinaki Forest Park, and a study of glossy black-cockatoos in Australia. The findings of all these studies supported the hypothesis that native animals benefit from possum control, but as concluded by Veltman, 'the evidence that possum control helps native forest animals is weak, perhaps because workers were constrained by logistical and financial reasons to gather data only from treated areas in a research-by-management approach'. The usefulness of such studies was considered limited since they may not have had sufficient baseline monitoring, may have used control methods that removed other pests, and may not have been conducted over a sufficient period of time to detect benefits. Instead, she argued a need for controlled studies in which the effects of possums are isolated from those of other pests.

The benefits of possum control to native fauna and flora have therefore not been well researched. The limited reliable data available suggest that possum control in general, and aerial poisoning in particular, are likely to be effective in conserving native biota and ecosystems threatened by possums, but clearly, there is a need for further, rigorously designed studies.

Assessment of environmental risks in relation to overall benefit. I believe the main risk associated with aerial poisoning operations concerns the secondary poisoning of dogs (Table 8.1), which typically are farm dogs. While this risk is manageable by ensuring that dogs are fitted with muzzles or prevented from wandering, a more hopeful long-term solution may be the incorporation of bacterial spores in baits to ensure rapid microbial degradation of the poison once a critical threshold of moisture is reached. Several species of bacteria are known to degrade fluoroacetate (Walker 1994). Risks to deer and pigs are controversial. Some hunters strongly argue against the use of aerial 1080 poisoning because of the possible impact on the hunting resource, but for conservation land (where most argument is focussed), the statutory requirement is for management that meets conservation goals rather than game-management goals. Additionally, since deer are a vector of bovine Tb, there is additional justification for reducing populations in certain areas. Mortality of individual native birds is undesirable but, perhaps, acceptable if removal of possums benefits populations in the longer term. Risks to human health are considered to be very small and manageable with recently introduced 'safe practice' procedures and monitoring programmes for industry workers. While it is not possible to compare the environmental risks and benefits directly, this review shows that the risks are either small, manageable, or fallacious. In comparison, the environmental benefits appear to be substantial although not well documented, and are considered to outweigh the limited risks.

8.3.4 Social factors

The use of 1080 poison for possum control, particularly when applied aerially, is an issue of wide interest in New Zealand society. This is not surprising as it is an activity that involves many people with a diversity of viewpoints. Farmers, conservationists, hunters, landowners, manufacturers, researchers, pest control contractors, and central and local government agencies may all have a very direct involvement in dealing with the problems caused by possums. Interest in 'the possum problem' is evidently also shared by many in the wider community, despite their lack of direct involvement, as two surveys of public perceptions (each involving >1000 respondents) have shown that 90% of New Zealanders consider the animal to be a serious pest (Sheppard & Urquhart 1991; Fitzgerald *et al*. 2000). Opinions are, however, less unanimous over the question of how best to control possums, which was studied in detail by Fitzgerald *et al*. (2000). Of the poisoning methods in use, aerial application of 1080 baits was the least publicly acceptable, with 54% of respondents considering it 'unacceptable', while ground-based application of 1080 baits was unacceptable to 43%. Respondents also perceived aerial use of 1080 to be the 'riskiest' control method with regard to the environment, the economy, and human health with 64%, 52% and 61% of respondents believing it to present 'moderate to high' risks respectively. A specific issue that probably accounts for much of the public disapproval of 1080 is the high risk towards dogs, especially since dogs, unlike possums, appear to suffer an unpleasant death. While research is continuing on the development of a true antidote, there is a need for wide dissemination of information on the treatment of dogs suspected to have consumed 1080 such as the simple emetic solutions of washing soda or salt discussed above (section 8.3.3).

That public perceptions do not align with scientific assessments, as summarised above, suggests that other influences help to shape public opinion. Indeed, a report by the Parliamentary Commissioner for the Environment (1994) that was undertaken in response to growing public concern over 1080 usage concluded that the public view of risks of using pesticides is influenced by a history of 'safe' chemicals eventually being shown to be unsafe or persistent (e.g. DDT, thalidomide, PCBs, Agent Orange etc.). Much of the discrepancy is therefore due to assumptions, lack of information, unwillingness to understand the issues, or misunderstanding. Furthermore deliberate misrepresentation of the issues is suspected by unethical individuals with undeclared motives, such as preventing the reduction of herds of game animals, or the detection of illicit marijuana crops by pilots and agency staff engaged in aerial operations. However, as Chess *et al.* (1988) (cited in Fitzgerald *et al.* 2000) advise in resolving risk issues, 'merely hammering away at the scientific information will rarely help', recommending instead a two-way participatory decision-making process. The success of this approach in the present context is exemplified by Fitzgerald *et al*. (2000) who involved focus groups in discussion of the acceptance of new biotechnology-based control methods for possums. When information on the scale and extent of the problem was introduced to discussion, individual positions on the acceptability of control technologies were often recast. As 12% of respondents to their questionnaire thought possums were native to New Zealand and a further 9% did not know, it would appear that decision making involving much more public participation should aim firstly to clearly articulate the costs and benefits of both the possum's existence in New Zealand and its control. Such 'risk communication' must involve a genuine effort to involve all parties for the purpose of making a consensus decision (Gough 1994). Practical steps were described by Hancox (1997) for effective consultation of the wider community during the planning of possum control.

Public participation in decision making appears to be increasing, particularly in relation to the claim that use of aerial 1080-poisoning forgoes the opportunity for employment in ground-based control and the harvesting of furs and meat for export. However, although most control work (and all aerial work) is now contracted out to private companies, fur retrieval is uneconomic for most due to the cost of revisiting areas. Furthermore, as indicated above, the presently-limited supply of suitably skilled operators to conduct the increasing amount of work available is already resulting in private contractors using aerial poisoning in the more inaccessible, and rugged terrain. Mindful of the needs for efficiency and risk-reduction, the Animal Health Board and Department of Conservation have encouraged the development of the private contracting industry through the coordinating agency, National Possum Control Agencies, which conducts a variety of industry training courses and technology transfer meetings. Collectively these organisations have provided technical information on possum control for the general public (e.g. Eason 2002; Green 2003) as well as research-based 'Best Practice' guides for use throughout the possum control industry (e.g. Henderson *et al.* 1999b).

Public perceptions overseas among consumers of New Zealand beef and dairy products are likely to be far more difficult to influence, leading to the suggestion that a phased withdrawal of 1080 may achieve greater short to medium-term acceptance of present use (Williams1994). However, I believe that pursuing such a policy would be unwise until a publicly acceptable alternative is available.

8.3.5 Overall assessment of the sustainability of aerial 1080 poisoning

This review suggests that the continued use of aerial 1080 poisoning following 'good practice' is desirable and justified on scientific grounds. 'Good practice' should entail the use of protocols such as those based on the research described in this thesis. These aim to ensure high-quality baits are delivered over targeted areas accurately and completely at specified, low application rates. Legal requirements (formerly described in the Pesticides (Vertebrate Pest Control) Regulations 1983) have been extended through the Resource Management Act 1991, Biosecurity Act 1993, Hazardous Substances and New Organisms Act 1996, and the Agricultural Compounds and Veterinary Medicines Act 1979. If these procedures and statutory requirements are followed, aerial application of 1080 is highly cost-effective, time-efficient, environmentally beneficial, and entails few significant risks. Of these, the risk towards dogs is considered to be the major source of informed public disapproval. The risk posed towards game animals is of debatable significance depending on one's viewpoint as, for example, a hunter, conservationist, farmer, or pest manager. Such issues should form part of the decision-making process in which public attitudes are recognised. Research suggests that with the opportunity to become more involved and better informed, public attitudes are likely to be more supportive of the use of aerial 1080 poisoning as a component of an integrated pest management strategy in which different approaches are combined.

The actual future of 1080 usage, at least in the short- to medium-term, is likely to be decided in 2004 through the Environmental Risk Management Authority (ERMA) reassessment process (J. Watson, ERMA, 30 June 2003, pers. comm.). This reassessment, requested jointly by the Animal Health Board and Department of Conservation, presents a major opportunity for public participation in decision making. It is expected that ERMA will be viewed as an independent authority with skills and procedures designed for assimilation of large numbers of submissions expressing opinion and presenting scientific data. Clearly the outcome of this review will determine the future use of 1080 in New Zealand, and most probably, the particular use of aerial application of 1080 baits for possum control.

8.4 Management uptake of research

A comprehensive, objective assessment of the extent to which my research findings have become incorporated in present possum management is beyond the scope of this thesis. However, I make the following observations based on my interaction with pest managers over the last 30 years.

8.4.1 Research findings that have been adopted

(1) Bait palatability and acceptance. Studies on the palatability and acceptance of baits (Chapter 2) showed that all bait types were generally accepted well despite differences in palatability, contrary to the widely held belief that palatability of different baits was the main factor in determining the level of success. This led to the selection of bait type being made more with respect to other considerations such as cost, availability, storage facilities etc. The bait acceptance method developed was also described in a manual of 'best practice' for pest managers (Henderson *et al*. 1999c) and is used occasionally where managers are concerned that success may be jeopardised by, for example, bait-shyness.

(2) Masking 1080. The discovery that 1080 is detected by a significant proportion of possums and the subsequent identification of suitable masks (Chapter 5) resulted in all 1080 baits eventually being treated with a mask (usually cinnamon oil because of its aversiveness to some bird species). This is described in the 'bait specifications' (Appendices 3 and 4) used by some pest managers. The high proportion of possums surviving through innate aversion to 1080 in baits suggested that this was previously one of the main constraints on operational success, and hence this aspect of my research is considered to have underpinned one of the main improvements in poisoning practice (not just aerial baiting practice).

(3) Complete coverage. The importance of the research demonstrating gaps in coverage leading to possum survival (Chapter 3) was recognised by some pest managers during the 1990s who began using, and helped to refine, navigational guidance systems. These early

systems proved somewhat unreliable and difficult to use and it was not until the end of the decade that cost-effective systems providing convenient bait-distribution mapping ability became available. As a result, use of Differential GPS became a standard requirement in all Animal Health Board and Department of Conservation operations in 2001. (Note: less costly, standard GPS systems, without differential correction, would now suffice as the accuracy-corrupting device previously used in the US-military-owned system was removed in 2001). This is regarded as a second major improvement in the effectiveness of aerial 1080 baiting.

(4) Reduced sowing rates. Following early trials that showed lower sowing rates to be effective there was a decline in sowing rate from earlier excessive rates to 5 kg/ha (pellets) and 10 kg/ha (carrot) resulting in major cost savings (Chapter 3). Nevertheless, most pest managers remained reluctant to further reduce application rates, which research had suggested was feasible. However, with the introduction of greater competition in the conduct of possum control during the late 1990s, pest managers have increasingly adopted lower application rates, especially since prefeeding has become common practice in 1080 operations. The protocols developed for calibration of sowing buckets and survey of bait-distribution have been adopted by some pest managers. With the emergence of new types of 'long-life' baits, it is likely that sowing rates will be reduced further, perhaps to less than 0.5 kg/ha. As described in Chapter 3, this research has led to major cost-savings enabling pest managers' budgets to be applied over a wider area and accelerating the progress towards operational goals.

(5) Seasonality of control effectiveness. Research on the (generally negligible) effect of season and habitat on likely control effectiveness (Chapter 5) has provided pest managers with a basis for conducting control in all but the warmest months, when possums' susceptibility to 1080 is reduced and, perhaps, at times when fruit-masting occurs (the impact of which could be predicted by rhodamine/bait acceptance trials immediately before a scheduled operation). The greater flexibility in scheduling operations underpinned by these findings has enabled bait manufacturers, aerial operators, and pest control agencies to meet the demand for an increasing amount of possum control. Additionally, my finding of the lack of a common seasonal effect on bait acceptance has eliminated one of the possible explanations for Veltman & Pinder's (2001) observation that 1080 kills are correlated with temperature; since seasonal bait acceptance remained consistently high throughout my study in three regions, it would appear that the correlation reflects a direct effect of temperature on

possums' susceptibility to 1080 rather than mediation through temperature-influenced food availability.

(6) Bait quality. In response to the research indicating that most baits were not lethal to most possums, the sole supplier of 1080 pellet baits introduced a larger-size pellet (mean = 12 g) in 1999. This has now become the main bait-type used in aerial control operations. It also enables achievement of bigger swath widths thus reducing operational flying costs. The importance of checking for correct 1080 content in baits was repeatedly stressed to pest managers at technology transfer seminars during the 1990s, and modifications to manufacturing plant in 1999 have resulted in pellets of more consistent size and 1080-content.

8.4.2 Research findings not fully adopted

(1) Sustaining control by mitigating bait-shyness. While aerial 1080 baiting is still predominantly utilised by relatively well-informed, experienced operators, much of the subsequent maintenance control is conducted by contractors who vary considerably in knowledge and expertise, as evidenced by a recent questionnaire (Coleman & Morgan 2002). Information on the potential for the four available poisons to induce bait shyness, and advice on its mitigation (Chapter 6) has evidently not been widely adopted by contractors yet. However, more rational sequential use of different control tools is likely as agencies are increasingly moving towards better documentation of control histories using GIS-databases, letting longer-term contracts that encourage improved strategic planning of control, and collaboration with contractors in the design of such longer-term control strategies.

(2) Reduced sowing rate for carrot bait. Although the sowing rate used for pellet baits has been greatly reduced such that a strategy of 2 kg/ha prefeed followed by 2 kg/ha toxic bait is now typical, carrot baits are evidently used at higher rates. This inconsistency evidently arises from the assumption that because carrot bait is considerably less expensive to prepare than pellet baits, operational managers are inclined to use higher sowing rates of carrot bait as a perceived 'insurance' against failure. However, excessive sowing rates will entail higher flying costs.

(3) Verification of baiting coverage. Presently most possum managers rely on GPS-derived output of flight paths to assess baiting coverage. This is unreliable as interruptions to bait-flow are not revealed. Until reliable systems for documenting bait distribution are available, field surveys are advisable, as described in Appendix 4. However, it is recognised that such

surveys will generally sample only a small proportion of the area treated and may detect only grossly inadequate baiting coverage.

8.5 Areas where further research is needed

While possum managers are now considerably better enabled to plan and implement effective aerial operations than they were in the early 1970s, this research has also revealed areas where there is a need for further investigation. These have been discussed in earlier chapters and are summarised here and prioritised according to my subjective assessment of where the greatest benefits remain to be realised. The priorities assigned are indicated as H (i.e. high), M (medium) and L (low).

8.5.1 Bait design

- Development of precision-dosed baits to minimise sublethal dosing, particularly at very low sowing rates. (*H*).
- Development of bait formulations with longer field-life. (*H*).
- Development of an effective antidote for 1080, particularly for treating poisoned dogs. (*H*).
- Evaluation of the characteristics of 12 g baits and the development of appropriate specifications. (*H*).
- Reduced risks of dog poisonings by use of moisture-activated bacteria to enhance biodegradation of 1080. (*M*).
- Further improvement in the quality of current baits by examination of the fragmentation of baits of different size and hardness during aerial application (particularly by helicopter). (*M*).
- Identification of alternative means of preventing possums' detection of 1080, such as microencapsulation, inhibition of taste receptors, or use of proteins to modify taste sensation. (*M*).
- Reassessment of the effectiveness of demethyltetracycline (DMCT) as a bait marker in possums and non-target species. (*L*).
- Further examination of the use of colour to deter native birds from feeding on baits. (*L*).

8.5.2 Bait delivery

- Validated systems for maximising complete bait coverage, identification of gaps for retreatment, and automatic over-riding of pilot-control of sowing equipment around GPS-identified sensitive areas such as watercourses. (*H*).
- Confirmation that some possums survive by remaining predominantly in the canopy, and development of bait types and distribution techniques to target the canopy or means of attracting canopy-dwellers to ground level. (*H*).
- Effect of climate (especially wind and rain) on possums' feeding behaviour. (*M*).
- Regulation of aerial sowing equipment for changes in windspeed and gradient. (*L*).
- Assessment of the suitability of the minimum bait-hardness specification in relation to bait-fragmentation (and, hence, possible increased risks of sublethal dosing of possums and non-target poisoning). (*L*).

8.5.3 Toxicology

- Development of target-specific toxicants that exploit metabolic pathways unique to maruspials, or perhaps, the brush-tailed possum. (*H*).
- Testing for the development of physiological resistance to 1080 in repeatedly exposed populations. (*M*).
- Persistence of cholecalciferol-induced bait-shyness. (*M*).
- Assessment of the need for higher concentrations of 1080 in bait to overcome temperature-related survival in warmer regions, and associated determination of the required concentration of masks. (*L*).
- The use of higher sugar content in baits to delay the onset of toxicosis, thus helping ensure that possums find and eat a lethal quantity of bait at low application rates. (*L*).
- Effect of harsh weather on possums' bait-feeding behaviour, and the consequent likelihood of sublethal poisoning. (*L*).

8.5.4 Control strategy and planning

- Cost-effectiveness of prefeeding assessed from operational data and based on kills and rate of population recovery. (*H*).

- Experimental assessment of the effect of prefeeding, lower sowing rates, and larger baits (12 g) on the subsequent by-kill of non-target species during aerial 1080 baiting. (*H*).
- Further updating of the pellet bait specifications to include 12 g pellets. (*H*).
- Identification and assessment of the influence of sharply-seasonal, ephemeral possum foods on operational effectiveness. (*M*).
- Long-term ('adaptive management') studies on the cost-effectiveness and environmental cost–benefits of control strategies in which aerial 1080 baiting is integrated with other control methods (including eventual use of biocontrol) over time. (*M*).
- Economic valuation of the agricultural production and indigenous biota protected by possum control to enable cost–benefit assessment. (*M*).
- Modelling of the hypothetical impact of genetically-based physiological and behavioural resistance to 1080. (*L*).
- Identification of regional variation in possum genotype associated with variations in bait preference as a basis for predicting optimum bait selection. (*L*).
- Identification of condition indices (as predictors of bait acceptance) that are more responsive to environmental stressors than body-fat-based indices. (*L*).

Acknowledgements

The thesis describes a wide range of studies that, over a long period, have been conducted with a great deal of help from many people, not all of whom I can now remember by name!

For many years I carried out the work as part of a group at Forest Research Institute led by Dr Jim Coleman. Jim, together with Wren Green, was inspirational in my early days through demonstrating what it takes to conceptualise and successfully implement a major field study of possums (at Lake Haupiri). This gave me the confidence to undertake large-scale field experiments in the rugged terrain of Westland at a time when most ecological research in New Zealand was of a descriptive nature. I benefited greatly from the intellectual stimulation of other colleagues at the Rangiora-based FRI, including Les Batcheler, Drew Peters, Morgan Williams, Jim Bell, Don Ross, Kees Pekelharing, John Martin, Eric Spurr, Ken Tustin, Malcolm Douglas, Malcolm Thomas, Chris Challies, John Parkes, Colin Clarke, and Chris Christie. I was also extremely fortunate in having the technical assistance of Ron Egan and Marty Sinclair for many years, and throughout many shared ordeals. Both eternally optimistic in the face of adversity, I think their approach is aptly summed up by Marty returning after an early morning start to set traps up the steep hillsides of the Taramakau Valley, and demanding another packload of 60 traps to get two days work done in one! Towards the end of this phase, I was introduced to my later-to-be supervisor, Graham Hickling. He immediately impressed me with a rapier-like mind softened by an engaging and most modest demeanour, characteristics which have been tremendously helpful to me in writing the thesis.

In later years, at Landcare Research, I benefited from a decade of close collaboration with Charlie Eason, another deceptively placid individual with a simmering intellect of Clutha dam proportions and output. Charlie's drive brought great vigour to the toxicological research in the FRI group that became part of Landcare Research in 1994, one of his many achievements being the splendid new animal facility and vastly improved laboratories. These facilities provided the opportunity for my research on possums' bait shyness, but the success of these studies is equally due to the extremely capable technical support of facility managers Lynne Milne and Julie Turner and their assistants, Andrea Airey, Penny Willcock, and Michael Wehner. The work was also greatly helped by the generous collegial spirit shown by Cheryl O'Connor of AgResearch, but then she must have known she would later become my boss on transferring to Landcare Research.

The research carried out by Peter Sweetapple and Jim Coleman (acknowledged in Chapter 4) and Ray Henderson (in Chapter 7) formed an integral part of the overall study. I am grateful for their leadership in particular aspects of the work in which I took a different role – does the word ‘budget’ remind you Ray?

Of the many other people who have helped me, I’d particularly like to thank: Tony Newton, Merv O’Reilly, Allan Farmer, Chris Main, and Derek Field (all of NZ Forest Service), Don McKenzie, Adrian Couchman, Bruce Waddell, Alan McRae, Paul Pripp, and Greg Napp (all of DOC), and Diedrik Meeken (Wellington Regional Council) for help in organising field work and arranging legions of willing and not-so-willing helpers; Peter O’Hara, Alistair Fairweather, Jeannie McInnes, Nick Hancox, Bill Martin, Maurice Kennedy, and James Ross for providing useful information; Jim Copland, Chris Frampton, Brian Fredric, Aaron McGlinchy, Wendy Ruscoe, and Ray Webster for keeping me on the statistical straight-and-narrow; Oliver Sutherland, my sister Jane Longmore, and my supervisor, Graham Hickling, for encouraging me to undertake this thesis and, together with Adrian Paterson, for providing helpful advice; and Landcare Research who, as a company, have generously allowed me time to complete unfinished pieces of work and to pull everything together.

My greatest thanks go to my wife Viv. She has accompanied me from Day 1 of this long journey, providing encouragement in those moments of doubt and anxiety (usually at three in the morning!) and tolerating my prolonged absences in the early days when Jennie and Rowan were either pouch young or backriders. Speaking of which, thanking the possum seems inappropriate, but I’d like to record my affection and respect for these wonderful animals that, sadly, found themselves in the wrong place.

References

Acord, B.R. (1992). Responses of the ADC program to a changing American Society. *Proceedings of the 15th Vertebrate Pest Conference*: 9-11.

Al-Omaran, M.F., Al-Suwayeh, S.A., El-Helw, A.M., & Saleh, S.I. (2001). Taste masking of diclofenac sodium using microencapsulation. *Journal of Microencapsulation, 19*: 45-52.

Alterio, N. (1996). Secondary poisoning of stoats (*Mustela erminea*), feral ferrets (*Mustela putorius*), and feral house cats (*Felis catus*) by the anticoagulant poison, brodifacoum. *New Zealand Journal of Zoology, 23*: 331-338.

Andrews, E.A., &. Braveman, N.S. (1975). The combined effects of dosage level and interstimulus interval on the formation of one-trial poison-based aversions in rats. *Animal Learning and Behaviour, 3*: 287-289.

Animal Control Products (2002). *Industry update, Summer/Autumn 2002*. Animal Control Products, Wanganui. 8 p.

Animal Control Products (2003). *Industry update, Winter 2003*. Animal Control Products, Wanganui. 8 p.

Animal Health Board (1993). *Animal Health Board Strategic Plan 1993-1998.* Animal Health Board, Wellington. 28 p.

Animal Health Board (1999). *Annual report for the year ending 30 June 1999.* Animal Health Board, Wellington. 36 p.

Animal Health Board (2000). Bovine tuberculosis pest management strategy 2001-2011. A discussion paper on the future options toward a Tb freeNew Zealand. Animal Health Board, Wellington. 63 p.

Animal Health Board (2001). Bovine tuberculosis national pest management strategy 2001-2013. An amendment proposal. Animal Health Board, Wellington. 61 p.

Anon., (1994). *Possum management in New Zealand.* Office of the Parliamentary Commissioner for the Environment, Wellington. 196 p.

Atzert, S.P. (1971). *A review of sodium monofluoroacetate (Compound 1080), its properties, toxicology, and use in predator and rodent control.* United States Department of the Interior Fish and Wildlife Services Special Scientific Report – Wildlife No. 146. 34 p.

Baddeley, C. (1985). *Assessment of wild animal abundance.* Forest Research Institute Bulletin No. 106, Christchurch. 46 p.

Bamford, J.M. (1970). Estimating fat reserves in the brush-tailed possum, *Trichosurus vulpecula* Kerr (Marsupialia: Phalangeridae). *Australian Journal of Zoology, 18*: 415-425.

Bamford, J.M., & Martin, J.T. (1971). A method for predicting success of aerial poisoning campaigns against opossums. *New Zealand Journal of Science, 14*: 313-321.

Barnett, S.A., Cowan, P.E., Radford, C.G., & Prakash, I. (1975). Peripheral anosmia and the discrimination of poisoned food by *Rattus rattus* (L.). *Journal of Behavioural Biology, 13*: 415-426.

Batcheler, C.L. (1958). Record and perspective of the proceedings of the meeting to discuss the noxious animals problem in New Zealand 1958. Unpublished New Zealand Forest Service report, Wellington. 51 p.

Batcheler, C.L. (1978). Compound 1080. Its properties, effectiveness, dangers and use. Report to the Minister of Forests and Minister of Agriculture and Fisheries. New Zealand Forest Service, Wellington. 68 p.

Batcheler, C.L. (1982). Quantifying "bait quality" from numbers of random encounters required to kill a pest. *New Zealand Journal of Ecology, 5*: 129-139.

Batcheler, C.L., & Cowan, P.E. (1988). *Review of the status of the possum in New Zealand.* Unpublished report. Forest Research Institute, Christchurch. 107 p.

Batcheler, C.L., Darwin, J.A., & Pracy, L.T. (1967). Estimation of opossum (*Trichosurus vulpecula*) populations and results of poison trials from trapping data. *New Zealand Journal of Science, 10*: 97-114.

Bell, J. (1972). The acute toxicity of four common poisons to the opossum (*Trichosurus vulpecula*). *New Zealand Veterinary Journal, 20*: 212-214.

Bertram, G. (1999). The economic impact on New Zealand of introduced pests. In: K. Hackwell and G. Bertram (Eds). *Pests and weeds – the cost of restoring the dawn chorus.* New Zealand Conservation Authority, Wellington. Pp. 45-71.

Bhardwaj, D., & I. Prakash. (1982). Discrimination between harmless and harmful stimulate by the house rat *Rattus rattus rufescens* (Gray). *Indian Journal of Experimantal Biology, 20*: 302.

Booth, L.H., Ogilvie, S.C., & Eason, C.T. (1999). Persistence of sodium monofluoroacetate (1080), pindone, cholecalciferol, and brodifacoum in possum baits under simulated rainfall. *New Zealand Journal of Agricultural Research, 42*: 529-531.

Bowen, L.H., Morgan, D.R., & Eason, C.T. (1995). Persistence of sodium monofluoroacetate (1080) in baits under simulated rainfall. *New Zealand Journal of Agricultural Research, 38*: 529-531.

Brown, J.A., & Arulchelvam, I.M. (1995). *The relative importance of operational factors on the success of aerial possum-control operations.* Unpublished Landcare Research Contract Report No. LC9596/60, Lincoln. 15 p.

Butcher, S. (2000). Impacts of possums on primary production. In: T. Montague (Ed.), *Possums in New Zealand: biology, impact and management of an introduced marsupial*. Lincoln, Manaaki Whenua Press. Pp. 105–110.

Caithness, T.A., & Williams, G.R. (1971). Protecting birds from poisoned baits. *New Zealand Journal of Agriculture, 122* (6): 38-43.

Challies, C.N. (1973). The use of physical size and growth rate for deer management. In: J. Orwin (Ed.), *Assessment and management of introduced animals in New Zealand forests.* Forest Research Institute Symposium *No. 14*, Rotorua. Pp. 44-54.

Chenoweth, M.B. (1949). Monofluoroacetic acid and related compounds. *Pharmacology Reviews 1*: 383-424.

Choquenot, D., & Parkes, J. (2000). Development of decision support systems for possum management. In: T. Montague (Ed.), *Possums in New Zealand: biology, impact and management of an introduced marsupial*. Manaaki Whenua Press, Lincoln. Pp. 271-277.

Choquenot, D., Bayliss, P., Parkes, J., & Hone, J. (2001). Bioeconomic analysis of pest management in production and conservation settings. *Proceedings of the 12th Australasian Vertebrate Pest Conference, Melbourne, 21-25 May 2001.* Pp. 260-265.

Clout, M.N. (1977). *The ecology of the possum (*Trichosurus vulpecula *Kerr) in New Zealand exotic pine forests.* Unpublished doctoral thesis, University of Auckland, Auckland.

Clout, M.N., & Barlow, N.D. (1982). Exploitation of brushtail possum popualtions in theory and practice. *New Zealand Journal of Ecology, 5*: 29-35.

Clout, M, & Eriksen, K. (2000). Anatomy of a distastrous success: the brushtail possum as an invasive species. In: T. Montague (Ed.), *Possums in New Zealand: biology, impact and management of an introduced marsupial*. Manaaki Whenua Press, Lincoln. Pp. 1-9.

Cockayne, L. (1928). Monograph on the New Zealand beech forests. Part 2. The forests from the practical and economic standpoints. *New Zealand State Forest Service bulletin No. 4.* Government printer, Wellington. 59 p.

Coleman, J. D., & Caley, P. (2000). Possums as a reservoir of bovine Tb. In: T. Montague (Ed.), *Possums in New Zealand: biology, impact and management of an introduced marsupial*. Manaaki Whenua Press, Lincoln. Pp. 92-104.

Coleman, J.D., & Morgan, D.R. (2002). *Knowledge gaps in conventional control of possums.* Unpublished Landcare Research Contract Report, *No. LC0203/021*, Lincoln. 32 p.

Coleman, J.D., Gillman, A., & Green, W.Q. (1980). Forest patterns and possum densities within podocarp/mixed hardwood forests on Mt Bryan O'Lynn Westland. *New Zealand Journal of Ecology, 3*: 69-84.

Coleman, J.D., Green, W.Q., & Polson, J.G. (1985). Diet of brushtail possums over a pasture-alpine gradient in Westland, New Zealand. *New Zealand Journal of Ecology, 8*: 21-35.

Coleman, J.D., Morgan, D.R., & Sweetapple, P. (1999). *Seasonal constraints on the use of aerially-sown baits loaded with 1080 to control possum populations*. Unpublished Landcare Research Contract Report *No. LC9899/123*, Lincoln. 21 p.

Collett, D. (1991). *Modelling binary data.* Chapman Hall, London. 408 p.

Cook, C.J., & Dean, J.M. (1996). Novel approaches for preventing behavioural resistance to pest management toxins. In: *Improving conventional control of possums.* The Royal Society of New Zealand Miscellaneous Series *No. 35,* Wellington. Pp. 57-61.

Corr, P.V. (1971). The acceptability and effectiveness of pellet baits for poisoning rabbits. *Australian Journal of Experimental Agriculture and Animal Husbandry, 11*: 407-414.

Cowan, P.E. (1977). Neophobia and neophilia: new-object and new-place reactions of three *Rattus* species. *Journal of Comparative and Physiological Psychology, 91*: 63-71.

Cowan, P.E. (1990). Brushtail possum. In: King, C.M. (Ed.), *The handbook of New Zealand mammals*. Oxford University Press, Auckland. Pp. 68-98.

Cowan, P.E. (1991). The ecological effects of possums on the New Zealand environment. In: *Symposium on tuberculosis*, Veterinary Continuing Education Publication *No. 132*, Massey University, Palmerston North. Pp. 73-88.

Cowan, P. (2000). Biological control of possums: prospects for the future. In: T. Montague (Ed.), *Possums in New Zealand: biology, impact and management of an introduced marsupial*. Manaaki Whenua Press, Lincoln. Pp. 262-270

Cowan, P.E., & Clout, M. (2000). Possums on the move: activity patterns, home ranges, and dispersal. In: T. Montague (Ed.), *Possums in New Zealand: biology, impact and management of an introduced marsupial*. Manaaki Whenua Press, Lincoln. Pp. 24-34

Cowan, P.E., & Waddington, D.C. (1990). Suppression of fruit production of the endemic forest tree, *Elaeocarpus dentatus*, by introduced marsupial brushtail possums, *Trichosurus vulpecula*. *New Zealand Journal of Botany, 28*: 217-224.

Cowan, P.E., Clark, J., Heath, D., Stankiewicz, M., & Meers, J. (2000). Predators, parasites, and diseases of possums. In: T. Montague (Ed.), *Possums in New Zealand: biology, impact and management of an introduced marsupial*. Manaaki Whenua Press, Lincoln. Pp. 82-91

Crabb, W.D., & Emik, L.O. (1946). Evaluating rat baits by field acceptance of oats on Guam. *Journal of Wildlife Management, 10*: 162-171.

Crier, J.K. (1970). Tetracyclines as a fluorescent marker in bones and teeth of rodents. *Journal of Wildlife Management, 34*: 829-834.

Day, T.D., & C.E. O'Connor (2000). Behavioural adaptation of brushtail possums (*Trichosurus vulpecula*) to captivity. *Animal Welfare, 9*: 413-420.

Day, T., O'Connor, C., & Matthews, L. (2000). Possum social behaviour. In: T. Montague (Ed.), *Possums in New Zealand: biology, impact andmanagement of an introduced marsupial*. Manaaki Whenua Press, Lincoln. Pp. 35-46.

Day, T.D., Matthews, L.R., & Waas, J.R. (2003). Repellents to deter New Zealand's North Island robin *Petroica australis longipes* from pest control baits. *Biological Conservation (in press).*

Department of Conservation (1994). *National plan for managing possums in New Zealand: a ten year plan 1993-2002*. Estate Protection and Policy Division, Department of Conservation, Wellington.

Department of Labour (2002a). *Guidelines for the safe use of sodium fluoroacetate (1080). Occupational* Safety and Health Service, Department of Labour, Wellington. 20 p.

Department of Labour (2002b). *Workplace exposure standards*. Occupational Safety and Health Service, Department of Labour, Wellington. 88 p.

Devine, C.D., & Cook, C.J. (1998). Bait shyness and its prevention in the rabbit *Oryctolagus cuniculus* L. *New Zealand Journal of Zoology, 25*: 223-229.

Douglas, G.W. (1959). Rabbit control by aerial baiting, effective new method. *Journal of the Department of Agriculture, Victoria, 57*: 145-158.

Dunnet, G.M., Harvie, A.E., & Smit, T.J. (1973). Estimating the proportions of various leaves in the diet of the opossum, *Trichosurus vulpecula* Kerr, by faecal analysis. *Journal of Applied Ecology, 10*: 737-745.

Eason, C.T. (2002). *Technical review of sodium monofluoroacetate (1080) toxicology*. Animal Health Board, Wellington. 31 p.

Eason, C.T., & Wickstrom, M. (2001). *Vertebrate pesticide toxicology manual.* Department of Conservation Technical Series *23*. Department of Conservation, Wellington. 122 p.

Eason, C.T., Gooneratne, R., Wright, G., Pierce, R., & Frampton, C.M. (1993). The fate of sodium monofluoroacetate (1080) in water, mammals, and invertebrates. *Proceedings of 46th conference of the New Zealand Plant Protection Society*: 297-301.

Eason, C.T., Henderson, R.J., Thomas, M.D., & Frampton, C.F. (1994). The advantages and disadvantages of sodium monofluoroacetate and alternative toxins for possum control. In: A.A. Seawright & C.T. Eason (Eds.), *Proceedings of the science workshop on 1080, Christchurch, 12-14 December 1993.* The Royal Society of New Zealand Miscellaneous Series *No. 28*, Wellington. Pp. 159-165.

Eason, C. T., Wright, G. R. G., & Gooneratne, R. (1999). Pharmacokinetics of antipyrine, warfarin and paracetamol in the brushtail possum. *Journal of Applied Toxicology 19*: 157-161.

Efron, B. (1981). Non-paramteric estimates of the standard error: the jack-knife, the bootstrap, and other methods. *Biometrika, 68*: 589-599.

Ekdahl, M.O., Smith, B.L., & Money, B.L. (1970). Tuberculosis in some wild and feral animals in New Zealand. *New Zealand Veterinary Journal, 18*: 44-45.

Elder, N.L. (1965). Vegetation of the Ruahine Range, an introduction. *Transactions of the Royal Society of New Zealand, 3*: 13-66.

Evans, J., & Griffith, R.E. (1973). A fluorescent tracer and marker for animal studies. *Journal of Wildlife Management, 37*: 73-81.

Fisher, P. (1998). *Rhodamine B as a marker for the assessment of non-toxic bait uptake by animals.* Melbourne: Vertebrate Pest Research Department, Victorian Institute of Animal Science, *Report Series No. 4*. 70 p.

Fitzgerald, A.E. (1984). Diet overlap between kokako and the common brushtail possum in central North Island, New Zealand. In: A.P. Smith & I.D. Hume (Eds), *Possums and gliders*. Australian Mammal Society, Sydney. Pp. 569-573

Fitzgerald, A.E., & Wardle, P. (1979). Food of the opossum *Trichosurus vulpecula* (Kerr) in the Waiho Valley, South Westland. *New Zealand Journal of Zoology, 6*: 339-345.

Fitzgerald, G., Wilkinson, R., & Saunders, L. (2000). Public perceptions and issues in possum control. In: T. Montague (Ed.), *Possums in New Zealand: biology, impact and management of an introduced marsupial*. Manaaki Whenua Press, Lincoln. Pp. 187-197.

Frampton, C.M., Warburton. B., Henderson, R., & Morgan, D.R. (1999). Optimising bait size and 1080 concentration (sodium monofluoroacetate) for the control of brushtail possums (*Trichosurus vulpecula*). *Wildlife Research, 26*: 53-59.

Fraser, W. (1985). Biology of the rabbit (Oryctolagus cuniculus (L)) in Central Otago, New Zealand with emphasis on its behaviour and its relevance to poison operations. Unpublished doctoral thesis, University of Canterbury, Christchurch.

Fraser, W. (2000). Possums as pests – the public perception. *Possum Research News No. 14*. Landcare Research, Lincoln. Pp. 8-9.

Galef, B.G.J. (1990). A historical perspective on recent studies of social learning about foods by Norway rats. *Canadian Journal of Psychology, 44*: 311-329.

Game Industry Board (2002, January 2003). Value of total deer industry exports. Retrieved 27 January 2003 from http://www.nzgib.co.nz/is/index.cfm

Garcia, J. (1989). Food for Tolman: cognitive and cathexis in concert. In: T.Archer & L.Nilson (Eds.), *Aversion, avoidance and anxiety: perspectives on aversely motivated behaviour*. Lawrence Erlbaum Associates, Erlbaum, Hillside, USA. Pp. 45-85.

Gilmore, D.P. (1965). Food of the opossum (*Trichosurus vulpecula*) in pastoral areas of Banks Peninsula, Canterbury. *Proceedings of New Zealand Ecological Society, 12,* 10-13.

Gilmore, D.P. (1967). Foods of the Australian opossum (*Trichosurus vulpecula* Kerr) on Banks Peninsula, Canterbury, and a comparison with other selected areas. *New Zealand Journal of Science, 10*: 235-279.

Godfrey, M.E.R. (1973). Carrot bait distribution within a swath and its significance in aerial poisoning. *New Zealand Journal of Experimental Agriculture, 1*: 323-328.

Gough, J.D. (1994). Risk communication and risk management. In: A.A. Seawright & C.T. Eason (Eds.), *Proceedings of the Science Workshop on 1080, Christchurch, 12-14 December 1993.* The Royal Society of New Zealand Miscellaneous Series *No. 28*, Wellington. Pp. 39-44.

Green, W.Q. (2003). *The use of 1080 to control possums and other pests.* Animal Health Board and Department of Conservation, Wellington. 49 p.

Greig-Smith, P.W. (1993). Killing with care – can pesticides be environmentally friendly. *Biologist, 40*: 132-136.

Grote, F.W., & Brown R.T. (1971). Conditioned taste aversions: two-stimulus tests are more sensitive than one-stimulus tests. *Behavioural Research Methods and Instruments, 3*: 311-312.

Gustavson, C.R. (1977). Comparative and field aspects of learned food aversions. In: L.M. Barker, M.R.Best, & M. Domjan (Eds.), *Learning mechanisms in food selection.* Baylor University Press, Waco, USA. Pp. 22-43.

Guyton, A.C., & Hall, J.E. (2000). *Textbook of medical physiology*. Saunders Company, Philadelphia. 1064 p.

Hancox, N. (1997). The need for consultation with the general public, iwi, and association. In: *Seminar proceedings on possum and mustelid control research*. National Possum Control Agencies, Wellington. Pp. 163-173.

Harrison, M. (1978). 1080. Wildlife. *A review, No. 9.* Wildlife Service, Department of Internal Affairs, Wellington. Pp. 48-53.

Hartley, L. (1999). Colour preferences in North Island robins (*Petroica australis*): implications for deterring birds from poisonous baits. *New Zealand Journal of Ecology, 23*: 255-259.

Hartley, L., Waas, J., O'Connor, C., & Matthews, L. (2000). Colour preferences and coloured bait acceptance by weka *Gallirallus australis*, an endemic New Zealand rail. *Biological Conservation, 93*: 255-263.

Hayes, W.J., & Laws, E.R. (1991*). Handbook of pesticide toxicology.* Academic Press, New York. 1576 p.

Hedderwick, G.W., & Will, G.M. (1982). Advances in the aerial application of fertilizer to New Zealand forests: use of an electronic guidance system and dust-free fertilizer. New Zealand Forest Research Institute Bulletin, No. 34, Rotorua. 16 p.

Henderson, R.J., & Frampton, C.M. (1999). *Avoiding bait shyness in possums by improved bait standards.* Unpublished Landcare Research Contract Report, *No. LC 9899/60*, Lincoln. 56 p.

Henderson, R.J., Morriss, G.A., & Morgan, D.R. (1997). The use of different types of toxic bait for sustained control of possums. *Proceedings of the 50th conference of the New Zealand Plant Protection Society*: 382-390.

Henderson, R.J., Frampton, C.M., Morgan, D.R., & Hickling, G.J. (1999a). The efficacy of baits containing 1080 for control of brushtail possums. *Journal of Wildlife Management, 63*: 1138-1151.

Henderson, R.J., Morgan, D.R., & Eason, C.T. (1999b). *Manual of best practice for ground control of possums.* Unpublished Landcare Research Contract Report, *No. LC9899/84*, Lincoln. 80 p.

Henderson, R.J, O'Connor, C.E., & Morgan, D.R. (1999c). *Current practices in sequential use of possum baits.* Department of Conservation Technical Series, *No. 22,* Department of Conservation, Wellington. 67p.

Hickling, G. J. (1994). Behavioural resistance by vertebrate pests to 1080 toxin: implications for sustainable pest management in New Zealand. In: A.A. Seawright & C.T. Eason (Eds.*), Proceedings of the science workshop on 1080. Christchurch, 12-14 December 1993.* The Royal Society of New Zealand Miscellaneous Series, *No. 28*, Wellington. Pp. 151-158.

Hickling, G. J. (1995). Implications of learned and innate behavioural resistance for single-tactic control of vertebrate pests. In: *Proceedings of the 10th Australian Vertebrate Pest Control Conference.* Pp. 303-308.

Hickling, G.J. (2001). Problems with application of risk assessment techniques to the management of vertebrate pests. In: *Proceedings of the 12th Australian Vertebrate Pest Control Conference.* Pp. 107-110.

Holloway, J.T. (1959). Noxious animal problems in the South Island watersheds. *New Zealand Science Review, 17:* 21-28.

Holmes, T. P., & Kramer, R.A. (1996). Contingent valuation of ecosystem health. *Ecosystem Health* 2: 56-60.

Hope, R.M. (1970). *Genetic variation in natural and laboratory populations of* Trichosurus vulpecula *and* Sminthopsis crassicaudata *(Marsupialia)*. Unpublished doctoral thesis, University of Adelaide, Adelaide.

Howard, W.E., Marsh, R.E., & Palmateer, S.D. (1973). Selective breeding of rats for resistance to sodium monofluoroacetate. *Journal of Applied Ecology, 10*: 731-737.

Howard, W.E., Marsh, R.E., & Cole, R.E. (1977). Duration of associative memory to toxic bait in deer mice. *Journal of Wildlife Management, 41*: 484-486.

Hurn, J. (1989). *GPS – a guide to the next utility*. Trimble Navigation, Sunnyvale, Califormia. 76 p.

Innes, J., Warburton, B., Williams, D., Speed, H., & Bradfield, P. (1995). Large-scale poisoning of ship rats (*Rattus rattus*) in indigenous forests of the North Island, New Zealand. *New Zealand Journal of Ecology, 19*: 5-18.

Ionescu, E., & Buresova, O. (1977). Failure to elicit conditioned taste aversion by severe poisoning. *Pharmacology, Biochemistry, and Behaviour, 6*: 251-254.

Jane, G. (1975). *Opossum bait acceptance trials.* Unpublished New Zealand Forest Service report, Forest Research Institute, Rotorua. 7 p.

Johnston, R.E. (1981). Attraction of odours in hamsters: an evaluation of methods. *Journal of Comparative and Physiological Psychology, 95*: 951-960.

Jolly, J.N. (1976). Habitat use and movements of the opossum in a pastoral habitat on Banks Peninsula. *Proceedings of the New Zealand Ecological Society, 23*: 70-76.

Jolly, S.E., R.J. Henderson, C. Frampton, & Eason, C.T. (1995). Cholecalciferol toxicity and its enhancement by calcium carbonate in the common brushtail possum. *Wildife Research, 22*: 579-583.

Kalmbach, E.R., & Welch, J.F. (1946). Coloured rodent baits and their value in safeguarding birds. *Journal of Wildlife Management, 10*: 353-360.

Kelton, S. (1995). Control technology application B what currently limits our effectiveness? In: C.F.J. O'Donnell (Ed.)*, Possums as conservation pests. Proceedings of a* *workshop, Christchurch, 29-30 November, 1994*. Department of Conservation, Wellington. Pp. 57-62.

Kininmonth, J.A. (1997). *A history of Forestry Research in New Zealand.* New Zealand Forest Research Institute, Rotorua. 271 p.

Kirk, H.B. (1920). *Opossums in New Zealand*. Government Printer, Wellington. 12 p.

Kirkby, R. J., & Williams, G. (1979). Behavior of marsupials: IV. Successive reversal learning in the brushtail possum (*Trichosurus vulpecula*). *Australian Journal of Psychology, 31*: 185-191.

Lindsey, G.D., Nass, R.D., & Hood, G.A. (1971). An evaluation of bait stations for controlling rats in sugarcane. *Journal of Wildlife Management, 35*: 440-444.

Linhart, S.B., & Gennelly, J.J. (1967). Fluorescent bone labelling of coyotes with demethylchlorotetracycline. *Journal of Wildlife Management, 31*: 317-321.

Littin, K.E., O'Connor, C.E., & Eason, C.T. (2000). Comparative effects of brodifacoum on rats and possums. *New Zealand Plant Protection, 53*: 297-301.

Livingstone, P.G. (1993). Production pests: what values need protection? *New Zealand Journal of Zoology, 20*: 273-277.

Lloyd, B. D., & McQueen, S.M. (2002). Measuring mortality in short-tailed bats (*Mystacina tuberculata*) as they return from foraging after an aerial 1080 possum control operation. *New Zealand Journal of Ecology, 26*: 53-60.

MacKenzie, J. (1997). A decision support system to assist in control of possums for Tb purposes. In: *Seminar proceedings on possum and mustelid control research*. National Possum Control Agencies, Wellington. Pp. 129-132.

MacNicoll, A.D., Dennis, N.J., Atterby, H., Hudson, A., Langton, S., Kerins, G.M., & Gill, J.E. (2001). Fitness effects of different alleles of the warfarin resistance gene – implications for resistance management. *Advances in Vertebrate Pest Management, 2*: 171-180.

Martin, J.T. (1973). Research into the control of opossums by aerial poisoning. In: J. Orwin (Ed.), *Assessment and management of introduced animals in New Zealand forests.* Forest Research Institute Symposium, *No. 14*, Rotorua. Pp. 153-158.

Mason, R. (1958). Foods of the Australian opossum (*Trichosurus vulpecula* Kerr) in New Zealand indigenous forest in the Orongorongo Valley, Wellington. *New Zealand Journal of Science, 1*: 590-613.

McDowall, R. (1994). Gamekeepers for the nation: the story of New Zealand's acclimatisation societies 1861-1990. Canterbury University Press, Christchurch. 508 p.

McGlinchy, A. (1996). Decision support tools for possum management. In: *Proceedings of the workshop: "Improving conventional control of possums", 25-26 October 1995.* The Royal Society of New Zealand, Miscellaneous Series, *No. 35*,Wellington. Pp. 35-38.

McIlroy, J.C. (1982). The sensitivity of Australian animals to 1080 poison. III. Marsupial and eutherian herbivores. *Australian Wildlife Research, 9*: 487-503.

McIlroy, J.C. (1983). The sensitivity of the brushtail possum (*Trichosurus vulpecula*) to 1080 poison. *New Zealand Journal of Ecology, 6*: 125-131.

Meat New Zealand (2002). Value of New Zealand exports 2000-2001. http://www.nzmeat.co.nz/wdbctx/corporate/exporting.home

Miller, J.G. (1974). The significance of preference in laboratory bait acceptance studies. *Proceedings of the 6th vertebrate pest conference*: 78-81.

Morgan, D.R. (1977). *Palatability trials of opossum baits.* Unpublished Protection Forestry report, *No. 152*. Christchurch: Forest Research Institute. 16 p.

Morgan, D.R. (1981). Monitoring bait acceptance in brush-tailed possum populations: Development of a tracer technique. *New Zealand Journal of Forestry Science, 11*: 271-277.

Morgan, D.R. (1981). Predation on a sparrow by a possum. *Notornis, 28*: 167-168.

Morgan, D.R. (1982). Field acceptance of non-toxic and toxic baits by populations of the brushtail possum (*Trichosurus vulpecula* Kerr). *New Zealand Journal of Ecology, 5*: 36-43.

Morgan, D.R. (1985). *Possum control – making toxic baits more acceptable*. What's New in Forest Research *No. 137*. Forest Research Institute, Rotorua. 4 p.

Morgan, D.R. (1988). Comparison of the effectiveness of hunting and aerial 1080 poisoning for controlling possums; and an evaluation of a navigation guidance system for improving aerial sowing of possum baits. Unpublished Forest Research Institute contract report, Christchurch. 22 p.

Morgan, D.R. (1990a). Behavioural responses of brushtail possums, *Trichosurus vulpecula*, to baits used in pest control. *Australian Wildlife Research, 17*: 601-613.

Morgan, D.R. (1990b). Effectiveness of an aerial-baiting treatment proposed for the Waipoua Forest possum-control programme: a pilot trial. Unpublished Forest Research Institute contract report, No. FWE 90/22, Christchurch. 12 p.

Morgan, D.R. (1993). Multi-species control by aerial baiting: a realistic goal? *New Zealand Journal of Zoology,20*: 367-372.

Morgan, D.R. (1994a). Improved cost-effectiveness and safety of sodium monofluoroacetate (1080) possum control operations. In A.A. Seawright & C.T. Eason (Eds.), *Proceedings of the Science Workshop on 1080, Christchurch, 12-14 December 1993.* The Royal Society of New Zealand Miscellaneous Series *No. 28*, Wellington. Pp. 144-150.

Morgan, D.R. (1994b). Improving aerial control of possums by precision bait delivery. *Proceedings of the 16th Vertebrate Pest Conference*: 287-292

Morgan, D.R. (1994c). Improving the efficiency of aerial sowing of baits for possum control. *New Zealand Journal of Agricultural Research, 37*: 199-206.

Morgan, D.R. (1995). Where should we be with possum control in 2005? – a researchers perspective. In C.F.J. O'Donell (Ed.). *Proceedings of a Workshop on Possums as Conservation Pests, Christchurch, 29-30 November 1994,* Possum and bovine Tb Control National Science Strategy Committee, Wellington. Pp.63-68.

Morgan, D.R. (2005). Long-life baits for enhancing maintenance control of possum populations. *Advances in Vertebrate Pest Management, 4*. (In press).

Morgan, D.R., Batcheler, C.L., & Peters, J. (1986). Why do possums survive aerial poisoning operations? *Proceedings of the 12th Vertebrate Pest Conference*: 210-214.

Morgan, D.R., Cook, C.J, & Devine, C. (1999). *Neurochemical alterations to prevent bait shyness in possums.* Unpublished Landcare Research Contract Report, *No. LC9900/56,* Lincoln. 15p.

Morgan, D.R., & Devine, C. (2001). *Efficacy of Agmatine as an appetite enhancer in possums, and the effect of prefeeding.* Unpublished Landcare Research Contract Report, *No. LC0102/47,* Lincoln. 9p.

Morgan, D.R., Eason, C.T. (2003). 1080: a review of its properties, lethal and sub-lethal effects, and primary and secondary non-target poisoning risks. *Advances in Vertebrate Pest Management,3.* (In press).

Morgan, D.R., Eason, C.T., & Wickstrom, M.L. (2001a). Zinc phosphide as a poison for possum control: the need for encapsulation. *Advances in Vertebrate Pest Management,2*: 337–344.

Morgan, D.R., Innes, J., Frampton, C., & Woolhouse, A.D. (1995). Responses of captive and wild possums to lures used in poison baiting. *New Zealand Journal of Zoology, 22*: 123-129.

Morgan, D.R., & Milne, L. (1997). Persistence of learned aversions by possums to 1080 baits and 'bait switching' as a solution. Unpublished Landcare Research Contract Report, No. LC9697/125, Lincoln. 10p.

Morgan, D.R., & Milne, L. (2002). Cholecalciferol-induced bait-shyness in possums (*Trichosurus vulpecula*). *International Journal of Pest Management, 48*: 113-19.

Morgan, D.R., Milne, L., O'Connor, C., & Ruscoe, W. (2001b). Bait shyness in possums induced by sub-lethal doses of cyanide paste bait. *International Journal of Pest Management, 47*: 277-284.

Morgan D.R., Morriss, G., & Hickling, G.J. (1996a). Induced 1080 bait-shyness in captive brushtail possums and implications for management. *Wildlife Research, 23*: 207-211.

Morgan, D.R., & Ross, J. (2001). Use of brodifacoum baits in relation to the development and mitigation of bait-shyness in the brushtail possum. *Proceedings of the 12th Vertebrate Pest Conference*:185-189.

Morgan, D.R., Thomas, M.D., & Meenken, D. (1996b). Optimising the aerial delivery of possum baits. In: *Proceedings of the workshop: "Improving conventional control of possums", 25-26 October 1995.* The Royal Society of New Zealand, Miscellaneous Series *No. 35*,Wellington. Pp. 70-74.

Morgan, D.R., Thomas, M.D., Meenken, D., & Nelson, P.C. (1997). Less 1080 bait usage in aerial operations to control possums. *Proceedings of the 50th conference of the New Zealand Plant Protection Society*: 391-396.

Morgan, D.R., & Warburton, B. (1987). *Comparison of the effectiveness of hunting and aerial 1080 poisoning for reducing a possum population*. Unpublished Forest Research Institute contract report, *No. FAE878001*, Christchurch. 24 p.

Moss, Z.N., O'Connor, C.E., & Hickling, G.J. (1998). Implications of pre-feeding on the development of bait aversions in brushtail possums *(Trichosurus vulpecula)*. *Wildlife Research,* 25: 133-138.

Murphy, E.C., & Bradfield, P. (1992). Change in diet of stoats following poisoning of rats in a New Zealand forest. *New Zealand Journal of Ecology, 16*: 137-140.

Murphy, E.C., Robbins, L., Young, J.B., & Dowding, J.E. (1999). Secondary poisoning of stoats after an aerial 1080 poisoning operation in Pureora Forest, New Zealand. *New Zealand Journal of Ecology 23*: 175-182.

Nachman, M., & Hartley, P. (1975). Role of illness in producing learned aversions in rats: a comparison of several rodenticides. *Journal of Comparative Physiological Psychology, 9*: 1010-1018.

National Possum Control Agencies (2002). *Protocol for possum population monitoring using the trap-catch method*. National Possum Control Agencies, Wellington. 32 p.

National Science Strategy Committee (2002). Draft National Science Strategy. National Science Strategy Committee for Possum and Bovine Tuberculosis Control,Wellington. 53p.

Nass, R.D., Hood, G.A., & Lindsey, G.D. (1971). Influence of gulch-baiting on rats in adjacent sugarcane fields. *Journal of Wildlife Management, 35*: 357-360.

Nelson, R.L., & Linder, R.L. (1972). Percentage of raccoons and skunks reached by egg baits. *Journal of Wildlife Management, 36*: 1327-1329.

New Zealand Forest Service (1982). Possums in captivity. *What's New in Forest Research No. 108*. Forest Research Institute, Rotorua. 4 p.

Norton, D. (2000). Benefits of possum control for native vegetation. In T. Montague (Ed.). *Possums in New Zealand. The biology, impact and management of an introduced marsupial*. Manaaki Whenua Press, Lincoln. Pp. 232-240.

O'Brien, P.H., Lukins, B.S., & Beck, J.A. (1988). Bait type influences the toxicity of sodium monofluoroacetate (Compound 1080) to feral pigs. *Australian Wildlife Research, 15*: 451-457.

O'Connor, C.E., Airey, A.T., & Littin, K.E. (2003). *Relative humaneness assessment of possum poisons.* Unpublished Landcare Research Contract Report, *No. LC0203/158,* Christchurch. 20 p.

O'Connor, C.E., & Matthews, L.R. (1997). Duration of cyanide-induced conditioned food aversions in possums. *Physiology & Behaviour, 62*: 931-933.

O'Connor, C.E., & Matthews, L.R. (1999). 1080-induced bait aversions in wild possums: influence of bait characteristics and prevalence. *Wildlife Research, 26*: 375-381.

Ogilvie, S.C., Thomas, M.D., Morriss, G.A., Morgan, D.R., & Eason, C.T. (2000). Investigation of sodium monofluoroacetate (1080) bait shyness in wild brushtail possum (*Trichosurus vulpecula*) populations. *International Journal of Pest Management, 46*: 77-80.

Oliver, A.J., & King, D.R. (1983). The influence of ambient temperature on the susceptibility of mice, guinea pigs, and possums to compound 1080. *Australian Wildlife Research 10*: 297-301.

Oliver, A.J., King, D.R., & Mead, R.J. (1977). The evolution of resistance to fluoroacetate intoxication in mammals. *Search, 8* (4): 130-132.

Oliver, A.J., Wheeler, S.H., & Gooding, C.D. (1982). Field evaluation of 1080 and pindone oat bait, and the possible decline in effectiveness of poison baiting for the control of the rabbit, *Oryctolagus cuniculus*. *Australian Wildlife Research, 9*: 125-134.

Orwin, J. (Ed). (1973). *Assessment and management of introduced animals in New Zealand forests.* Forest Research Institute Symposium, *No. 14*, Rotorua. 191 p.

Overton, A.S., Margraf, F.J., Weedon, C.A., Pieper, L.H., & May, E.B. (2003). The prevalence of mycobacterial infections in striped bass in Chesapeake Bay. *Fisheries Management and Ecology, 10*: 301-308.

Ozoga, J.J., & Verme, L.J. (1978). The thymus gland as a nutritional status indicator in deer. *Journal of Wildlife Management, 42*: 791-798.

Packham, C.J. & Connolly, G. (1992). Control methods research priorities for animal damage control. *Proceedings of the 15th Vertebrate Pest Conference*: 12-16.

Parkes, J.P. (1990). *Procedures for ranking and monitoring feral goat (*Capra hircus*) control*. Unpublished Forest Research Institute contract report, *No. FWE 90/11*, Christchurch. 45 p.

Parkes, J.P., Robley, A., Forsyth, D., & Choquenot, D. (2003). Adaptive management experiments in vertebrate pest control in New Zealand and Australia. *Wildlife Society Bulletin*. (In press).

Parliamentary Commissioner for the Environment (1994). *Possum management in New Zealand*. Office of the Parliamentary Commissioner for the Environment, Wellington. 196 p.

Pass, D.M., Foley, W.J., & Bowden, B. (1998). Vertebrate herbivory on *Eucalyptus* identification of specific feeding deterrents for common ringtail possums

(*Pseudocheirus peregrinus*) by bioassay guided fractionation of *Eucalyptus ovata* foliage. *Journal of Chemical Ecology, 24*: 1513-1527.

Payton, I. (2000). Damage to native forests. In: T. Montague (Ed.), *Possums in New Zealand: biology, impact and management of an introduced marsupial*. Manaaki Whenua Press, Lincoln. Pp. 111-125.

Payton, I.J., Pekelharing, C.J., & Frampton, C.M. (1997). *Foliar browse index: a method for monitoring possum damage to forests and rare or endangered plant species.* Unpublished Landcare Research Contract Report, *No. LC9697/60,* Christchurch. 62 p.

Pekelharing, C.J. (1974). *Bait development- interim report No. 2.* Unpublished Forest and Range Experimental Station report, New Zealand Forest Service, Rangiora. 12 p.

Pekelharing, C.J. (1979). Fluctuation in opossum populations along the north bank of the Taramakau catchment and its effect on the forest canopy. *New Zealand Journal of Forestry Science, 9*: 212-224.

Pelz, H.-J., Hänisch, D. & Lauenstein, G. (1995). Resistance to anticoagulant rodenticides in Germany and future strategies to control *Rattus norvegicus*. *Pesticide Science*, *43*: 61-67.

Peters, J.A. (1975). Contamination of forest ecosystems by sodium monofluoroacetate (Compound 1080). *Proceedings of the 22^nd^ conference of the New Zealand Ecological Society*: 34-41.

Peters, J.A., & Fredric, B.J. (1982). *Susceptibility of the brushtail possum (*Trichosurus vulpecula*) to sodium monofluoroactetate (compound 1080).* Unpublished New Zealand Forest Service report, Christchurch. 23 p.

Perham, A.N. (1924). *Progress report of investigation of the opossum - genus Trichosurus in New Zealand.* Unpublished New Zealand State Forest Service report, Wellington. 10 p.

Pollard, J.S., & Lysons, A.M. (1967). Possums in the closed field test. *Animal Behaviour*,*15:* 129-133.

Powlesland, R.G., Knegtmans, J.W., & Styche, A. (2000). Mortality of North Island tomtits (*Petroica macrocephala toitoi*) caused by aerial 1080 possum control operations, 1997-98, Pureora Forest Park. *New Zealand Journal of Ecology, 24*: 161-168.

Pracy, L.T. (1961). *Aerial poison trials for opossum control and development*. Unpublished New Zealand Forest Service report, Wellington. 10 p.

Pracy, L.T. (1974). *Introduction and liberation of the opossum (*Trichosurus vulpecula*) into New Zealand*. New Zealand Forest Service Information Series, *No. 45*, Wellington. 28 p.

Pracy, L.T. (1975). Opossums. *New Zealand Nature Heritage, 3*: 873-882.

Pracy, L.T. (1981). Opossum survey. *Counterpest, 5*: 5-15.

Pracy, L.T., & Kean, R.I. (1949). Control of possums an urgent problem. *New Zealand Journal of Agriculture, 78*: 469-480.

Pracy, L.T., Robertson, B.A., & Udy, P.B. (1982). Flavours tested on Kapiti. *Counterpest, 8*: 10-11.

Prakash, I. (1988). Bait shyness and poison aversion. In: Prakash, I. (Ed.), *Rodent pest management*. CRC Press, Boca Raton. 480 p.

Prasad, G. (2001). Length-weight relationships of *Penaeus monodon* reared in semi-intensive culture sytems of Keral, India. *Naga, 24*: 16-17.

Prescott, C.V., El-Amin, M., & Smith, R.H. (1992). Calciferols and bait shyness in the laboratory rat. *Proceedings of the 15^th Vertebrate Pest Conference*: 218-223.

Rammell, C.G., & Fleming, P.A. (1978). Compound 1080: properties and use of sodium monofluoroacetate in New Zealand. Ministry of Agriculture and Fisheries, Wellington. 137 p.

Ramsey, D. L. (1999). Effects of fertility control on the population dynamics and behaviour of possums. In: Sutherland, G. (Ed.), *Advances in the biological control of possums: report of a workshop sponsored by the National Science Strategy Committee for Possum & Bovine Tb Control, 13-15 April 1999*. The Royal Society of New Zealand Miscellaneous Series *No. 56*, Wellington. Pp. 80-84.

Reichardt, P.B., Bryant, J.P., Anderson, B.J., Phillips, D., Clausen, T.P., Meyer, M., & Frisby, K. (1990). Germacrone defends Labrador tea from browsing by snowshoe hares. *Journal of Chemical Ecology, 16*: 1941-1959.

Riley, A.L., & Clarke, C.M. (1977). Conditioned taste aversions: a bibliography. In: L.M. Barber, M. Ben, & M. Donjan (Eds.), *Learning, mechanisms in food selection*. Baylor University Press, Waco, Texas. Pp. 593-616.

Rogers, J.G. (1978). Repellents to protect crops from vertebrate pests: some considerations for their use and development. In: R.W. Bullard (Ed.), *Flavour chemistry of animal* *foods*. American Chemical Society Symposium Series, *No. 67*, Washington D.C. Pp. 150-184.

Ross, J.G. (1999). *Cost-effective control of 1080 bait-shy possums* (Trichosurus vulpecula). Unpublished doctoral thesis, Lincoln University, Lincoln.

Ross, J.G., Hickling, G.J., & Morgan, D.R. (1997). Use of subacute and chronic toxicants to control sodium monofluoroacetate (1080) bait shy possums. *Proceedings of the 50th conference of the New Zealand Plant Protection Society*: 397-400.

Ross, J.G., Hickling, G.J., Morgan, D.R., & Eason, C.T. (2000). The role of non-toxic prefeed and postfeed in the development and maintenance of 1080 bait shyness in captive brushtail possums. *Wildlife Research, 27*: 69-74.

Rowley, I. (1958). Behaviour of a natural rabbit population poisoned with "1080". *CSIRO Wildlife Research, 3*: 32-39.

Rowley, I. (1963). Bait materials for poisoning rabbits II. A field study of the acceptance of carrots and oats by wild populations of rabbits. *CSIRO Wildlife Research, 8*: 62-77.

Roy, G. (Ed.) (1997). *Modifying bitterness - mechanism, ingredients, and applications.* Culinary and Hospitality Industry Publications Services, Weimar, Texas. 332 p.

Rzoska, J. (1954). The behaviour of white rats towards poison baits. In: D. Chitty (Ed), *Control of rats and mice. Vol. 2*. Clarendon Press, Oxford. Pp. 374-395.

Royal Society of New Zealand (1998). *Biological control of possums in New Zealand.* The Royal Society of New Zealand, Miscellaneous series, *No. 45,* Wellington. 129 p.

Sadleir, R. (2000). Evidence of possums as predators of native animals. In: T. Montague (Ed.), *Possums in New Zealand: biology, impact and management of an introduced marsupial.* Manaaki Whenua Press, Lincoln. Pp.126-131.

Samson, A., & Green, K. (2003). *On the mountain – a lead article*. Conservation Science Newsletter, *No. 48*, Department of Conservation, Wellington. Pp. 1-4.

Sheppard, R., & Urquhart, L. (1991). *Attitudes to pests and pest control methods.* Agribusiness and Economics Research Unit, Research Report *No. 210*, Lincoln University, Lincoln. 69 p.

Sinclair, R.G., & Bird, P.L. (1984). The reaction of *Sminthopsis crassicaudata* to meat baits containing 1080: implications for assessing risk to non-target species. *Australian Wildlife Research, 11*: 501-507.

Sokal, R.R., & Rohlf, F.J. (1973). *Introduction to biostatistics*. W.H. Freeman, San Francisco. 368 p.

Southwood, T.R.E. (1966). *Ecological methods.* Methuen, London. 391 p.

S-PLUS (2001). S-*Plus for Windows guide to statistics, Volume 1 Guide*. *Vers. 6*. Insightful Corporation, Seattle. Available: http://www.insightful.com/support/documentation.asp?DID=1

Spragg, W.T., & Fox, R.E. (1974). The use of a radioactive tracer to study the nesting system of *Mastotermes darwiniensis* Froggatt. *Insectes Sociaux, 21*: 309-316.

Spurr, E.B. (1981). Modelling and effects of control operations on possum *Trichosurus vulpecula* populations. In: B.D.Bell (Ed.), *Proceedings of the first symposium on marsupials in New Zealand, Wellington, 9-10 May 1974.* Victoria University, Wellington. Pp. 223-234.

Spurr, E.B. (1993). Review of known effects of 1080 in possum control operations using carrot and cereal baits on non-target species in New Zealand. Unpublished Landcare Research contract report No. LC9394/35, Christchurch. 40 p.

Spurr, E. B. (2000). Impacts of possum control on non-target species. In: T. Montague (Ed.), *Possums in New Zealand, biology, impact and management of an introduced marsupial.* Manaaki Whenua Press, Lincoln. Pp.175-186.

Spurr, E.B. (2002). *Bait buckets for helicopters*. Unpublished Landcare Research contract report, *No. LC0102/62,* Lincoln. 23 p.

Steel, R.G.D., & Torrie, J.H. (1960). *Principles and procedures of statistics*. McGraw-Hill, New York. 481 p.

Sullins, G.L., & Verts, B.J. (1978). Baits and baiting techniques for control of Belding's ground squirrels. *Journal of Wildlife Management, 42*: 890-896.

Taylor, J.A. (1979). The foods and feeding habits of subadult *Crocodylus porosus* Schneider in northern Australia. *Australian Wildlife Research, 6*: 347-359.

Taylor, K.D., & Quy, R.J. (1973). Marking systems for the study of rat movements. *Mammal Review, 3*: 30-34.

Thomas, M.D., & Morgan, D.R. (1996). *Reduced aerial application rates of 1080 bait for possum control: a feasibility study.* Unpublished Landcare Research contract report, *No. LC9596/103,* Lincoln. 6 p.

Tilley, M.W., Doolittle, J.H., & Mason, D.J. (1966). Olfactory discrimination learning in the Virginia opossum. *Perception and Motor Skills, 23*: 845-846.

Turner, J.C. (1969). Cyanide detoxification in the opossum (*Trichosurus vulpecula*). *New Zealand Journal of Science, 12*: 569-575.

Twigg, L.A., Martin, G.R., & Lowe, T.J. (2002). Evidence of pesticide resistance in medium-sized mammalian pests: a case study with 1080 poison and Australian rabbits. *Journal of Applied Ecology, 39*: 549-560.

Veltman, C. (2000). Do native wildlife benefit from possum control? In: T. Montague (Ed.), *Possums in New Zealand, biology, impact and management of an introduced marsupial.* Manaaki Whenua Press, Lincoln. Pp.175-186.

Veltman, C.J., & Pinder, D.N. (2001). Brushtail possum mortality and ambient temperatures following aerial poisoning using 1080. *Journal of Wildlife Management, 65*: 476-481.

Walker, J.R.L. (1994). Degradation of sodium monofluoroacetate by soil micro-organsims. In: A.A. Seawright & C.T. Eason (Eds)*, Proceedings of the science workshop on 1080, Christchurch, 12-14 December 1993.* The Royal Society of New Zealand Miscellaneous Series *No. 28*, Wellington. Pp. 50-53.

Walters, B., & Bloomfield, T.E. (1991). Dining out with Peter Rabbit. *Proceedings of the 9th Australian Vertebrate Pest Conference*: 129-132.

Warburton, B. (1978). Foods of the Australian brush-tailed opossum (*Trichosurus vulpecula*) in an exotic forest. *New Zealand Journal of Ecology, 1*: 126-131.

Warburton, B. (1996). *Trap-catch for monitoring possum populations.* Unpublished Landcare Research contract report, *No. LC9596/60* , Lincoln. 15 p.

Warburton, B., Poutu, N., & Domigan, I. (2001). The Bulldog – an effective new kill-trap. *Possum Research News No. 16.* Landcare Research, Lincoln. Pp. 1-2.

Ward, D. (1979). Habitat use and home range of radio-tagged opossums *Trichosurus vulpecula* Kerr in New Zealand lowland forest. In: G.C. Montgomery (Ed.), *The ecology of arboreal folivors. Proceedings of National Zoological Park.* Smithsonian Institute Press, Washington. Pp. 267-287.

Wardle, J.A. (1984). *The New Zealand beeches: ecology, utilisation and management*. Wellington, New Zealand Forest Service. 447 p.

Watts, M. (1994). *The poisoning of New Zealand*. Auckland Institute of Technology Press, Auckland. 224 p.

Weber, D.D., & Ridgway, G.J. (1962). The deposition of tetracycline drugs in bones and scales of fish and its possible use for marking. *Progressive Fish-Culturist, 24*: 150-155.

Westbrooke, I.A., Etheridge, N.D., & Powlesland, R. G. (2003). Comparing methods for assessing the mortality impacts of an aerial 1080 pest control operation on tomtits (*Petroica macrocephala toitoi*) in Tongariro Forest. *New Zealand Journal of Ecology, 27*: 115-123.

Wheeler, S.H., & Hart, D.S. (1979). The toxicity of sodium monofluoroacetate to wild rabbits, *Oryctolagus cuniculus* (L.), in Australia. *Australian Wildlife Research, 5*: 79-84.

Williams, C.K., & Turnbull, H.L. (1983). Variations in seasonal nutrition, thermoregulation and water balance in two New Zealand populations in the common brushtail possum, *Trichosurus vulpecula* (Phalangeridae). *Australian Journal of Zoology, 31*: 333-343.

Williams, J.M. (1994). Food and fibre markets and societal trends: implications for pest management. In A.A. Seawright & C.T. Eason (Eds*.), Proceedings of the science workshop on 1080, Christchurch, 12-14 December 1993.* The Royal Society of New Zealand Miscellaneous Series *No. 28*, Wellington. Pp. 20-32.

Witty, M. (1998). New technologies for taste modifying proteins. *Trends in Food Science and Technology, 9*: 275-280.

Woodhouse, G. (2002). Adapting GIS technology to get better results from aerial possum control operations. In: *Making current technology more effective, National Technology Transfer Seminar, November 18-19, 2002.* National Possum Control Agencies, Wellington. Published on CD.

Yagi, T., Nishiwaki, M., & Nakajima, M. (1963). A preliminary study of the method of time marking with lead salt and tetracycline on the teeth of fur seal. Whales Research Institute, Scientific Report No 17.

Zar, J.H. (2002). *Biostatistical analysis*. Fourth Edtion. Prentice Hall International, Pearson Education, Upper Saddle River, New Jersey. 663 p.

Appendix 1. Geographical coordinates of study locations using the NZ Map Grid system

Study location (in order of appearance in text)	Reference to section in text	NZ Map Grid coordinates at centre of study location
Omihi, North Canterbury	Table 2.2	2505525E, 5792625N
Deception Valley, Westland	Table 2.2	2396910E, 5822325N
Bullock Creek, Westland	Table 2.2	2378350E, 5900350N
Hokonui Hills, Southland	Table 2.2	2167750E, 5443050N
Lake Haupiri, Westland	Tables 2.2 and 2.5	2404650E, 5842150N
Harper Valley, Canterbury	Table 2.2	2393400E, 5781600N
Taipo Valley, Westland	Table 2.5	2386585E, 5822355N
Kaingaroa Forest, Bay of Plenty	Table 2.5	2828300E, 6307300N
Taramakau Valley, Westland	Table 2.5	2395400E, 5825450N
Wainihinihi Creek, Westland	Section 2.5.2	2367950E, 5819150N
Granite Hill, Westland, block 1	Table 3.1	2397825E, 5839825N
Granite Hill, Westland, block 2	Table 3.1	2398900E, 5840525N
Granite Hill, Westland, block 3	Table 3.1	2399725E, 5841525N
Copland Valley, Westland	Table 3.1	2257575E, 5728775N
Pureora Forest, Waikato	Table 3.1	2733525E, 6313525N
Slopedown Forest, Southland	Table 3.1	2240100E, 5416850N
Waipoua Forest, Northland	Table 3.1	2558000E, 6618850N
Waimihia Forest, Bay of Plenty	Section 3.3.1	2794450E, 6260625N
Titiraupanga, Bay of Plenty	Table 3.9	2761300E, 6287500N
Rangitoto Range, Waikato	Table 3.9	2737300E, 6266400N
Moerangi, Waikato	Table 3.9	2731950E, 6252250N
West Taupo, King Country	Table 3.9	2745650E, 6269050N
Waipoua Forest, Northland	Tables 3.9 and 3.10	2559500E, 6620400N
Mount Egmont, Taranaki	Table 3.9	2608600E, 6212400N
Waimihia Forest, Bay of Plenty	Table 3.10	2795775E, 6264625N
Puketi Forest, Northland	Table 3.10	2573550E, 6664250N
Puketiro, Wellington	Table 3.10	2740325E, 6010500N
Whakatikei, Wellington	Table 3.10	2681890E, 6010430N
Otaki River, Wellington	Table 3.10	2703700E, 6033025N
Herekino Forest, Northland	Section 4.2.1	2532450E, 6668350N
Moki Forest, Taranaki	Section 4.2.1	2663625E, 6248090N
Cobb Valley, Nelson	Section 4.2.1	2476635E, 6008820N
Waipara Gorge, North Canterbury	Section 6.2.1	2475485E, 5795305N

Appendix 2. Possum-preferred plant species monitored in each of the three study areas used for seasonal bait acceptance trials (Chapter 4)

Herekino Forest

Taraire (*Beilschmiedia tarairi*)

Kohekohe (*Dysoxylum spectabile*)

Rewarewa (*Knightia excelsa*)

Mahoe (*Melicytus ramiflorus*)

Northern rata (*Metrosideros robusta*)

Totara (*Podocarpus totara*)

Five-finger (*Pseudopanax arboreus*)

Lancewood (*Pseudopanax crassifolius*)

Nikau (*Rhopalostylis sapida*)

Towai (*Weinmannia silvicola*)

Lacebark (*Hoheria populnea*)

Toro (*Myrsine salicina*)

Moki Forest

Tawa (*Beilschmiedia tawa*)

Hinau (*Elaeocarpus dentatus*)

Rewarewa (*Knightia excelsa*)

Mahoe (*Melicytus ramiflorus*)

Northern rata (*Metrosideros robusta*)

Totara (*Podocarpus totara*)

Lancewood (*Pseudopanax crassifolius*)

Supplejack (*Ripogonum scandens*)

Kamahi (*Weinmannia racemosa*)

Pigeonwood (*Hedycarya arborea*)

Toro (*Myrsine salicina*)

Cobb Valley

Lancewood (*Pseudopanax crassifolius*)

Tree fuchsia (*Fuchsia excorticata*)

Wineberry (*Aristotelia serrata*)

Marbleleaf (*Carpodetus serratus*)

Pokaka (*Elaeocarpus hookerianus*)

Bush lawyer (*Rubus cissoides*)

Small-leaved coprosmas (*Coprosma* spp.)

Herbs (herbaceous species on forest floor)

Southern rata (*Metrosideros umbellata*)

Pseudopanax simplex

Pseudopanax linearis

Melicytus lanceolatus

Appendix 3. Specifications for cereal pellet baits used in aerial control operations

Specifications for "1080 cinnamon lured pollard possums baits" were originally developed in 1987 for MAFQual by an interdepartmental group of scientists comprising C.L. Batcheler, J.D. Coleman and myself (Ministry of Forestry), and J. Bell, D. Ross, and J.M. Williams (MaFTech), with subsequent input from I. Logan (Animal Control Products). These specifications have been updated following the recent evaluations of bait quality by Henderson & Frampton (1999) and are presented below. Note, however, the specifications need further revision following the introduction of 12 g baits by Animal Control Products in 1999.

Specifications for cinnamon-masked 1080 pellet baits

General: Baits shall be grain-based, regular in shape, poisoned with monofluoroacetate (1080), masked with cinnamon, and coloured green. The cereal grain for bait manufacture should contain no more than 13% moisture, and have less than 5% screenings. Before pelleting the grain shall be milled with a screen not exceeding 3 mm, so most particle sizes fall in a range 0.25-0.50 mm. An approved biscuit grade of wheat is recommended for optimal binding of pellet ingredients. To prevent 'sweating' of recently manufactured cereal baits, they must be cooled to a temperature of no more than 8ºC above ambient room temperature before they are packaged.

Palatability: The palatability of toxic bait should exceed 40% compared to recently manufactured non-toxic RS5 bait (of similar size).

Efficacy: When 40 individually caged possums are presented paired trays containing 100 g of bait containing 0.15% 1080 and 100 g of non-toxic RS5 bait at least 90% of possums shall eat a lethal amount of toxic bait. To ensure most animals are killed quickly and humanely, it is recommended that a minimum of 35 of 40 caged possums eat at least 8 g of bait (i.e. the amount of bait that administers 4 mg/kg of 1080 to a 3-kg possum).

Fracture/breakage/dust and bait hardness: Dust and fragments (i.e. pieces less than 1 g) shall comprise no more than 5% by weight.

Size: Baits used during aerial control operations shall have a mean weight not less than 6 g. The standard deviation of 50 individually weighed baits should not exceed 1 g (one gram), with 95% of baits by weight weighing more than 4 g.

Hardness: A pointed 2-mm-diameter probe shall penetrate baits when the mean pressure applied to the side-walls of 40 large (6 g) baits is 5-12 kg; or when 2-7 kg is applied with a pointed probe to the side-walls of 40 small (1.5 g) RS5 baits. The standard deviation of 40 baits shall not exceed ±5 kg pressure, with 95% of baits penetrated with 2-15 kg of pressure on the probe.

Toxin: The toxin, 1080, used in baits shall be at least 93% pure sodium monofluoroacetate and contain less than 0.25% inorganic fluoride. The pH of a 0.1% aqueous solution of the 1080 powder shall be 6.5 or less.

1080 concentration: The concentration of 1080 in samples of 10 baits shall be 1.5 ± 0.22 mg/g (i.e. all samples should have a concentration within 15% of the nominal concentration). The means of 10 or more such samples shall lie within ±5% of the nominal concentration. The concentration in 90% of 10 individual baits shall be within ±25% of the nominal concentration.

Colour: A green colour shall be incorporated into the bait to ensure it has a colour range of 221-267 by the New Zealand Standard Specification 7702 (section 23, Standards Act 1965). Surface colour shall be 98% or more of the surface area when tested by intercepts on a dot grid 1 cm x 1 cm over a random sample of not less than 100 baits.

Masks: Food-grade cinnamon flavour (Bush, Boake and Allen, Auckland; Product No. 02-7780) in monopropylene glycol with a specific gravity of 1.05 shall be mixed into baits at 0.2% wt/wt to mask the taste and odour of 0.15% 1080. Cinnamon concentrations should never be less than 0.1% or more than 0.5% wt/wt.

Stability: Baits shall be stored for no longer than 6 months with a moisture content of 12%, 3 months with a moisture content of 14%, and less than a month with a moisture content of 16%. Baits shall have a mould count less than 400 cfu/g. Bait should be stored in a cool, dry storeroom containing few micro- and macro-organisms.

Leaching: Baits shall retain 80% or more of their toxic loading after 5 mm of rainfall over 24 hours.

Storage and stacking of 1080 pellets: Bait shall be stored in a clean, dry, locked enclosure until it is used. Pallets of bait shall be stacked no more than two high during transport and storage.

Appendix 4. Specifications for 1080 carrot baits used in aerial possum control operations

Draft specifications for "the preparation of masked 1080 carrot baits for aerial application" were originally prepared by myself in October 1993, with subsequent input from P. Livingstone (AHB), P.C. Nelson (Pest Management Services), I. Lucas (Canterbury Regional Council), N. Hutchins (Environment Waikato), N. Powell (Otago Regional Council). These specifications have been updated following the recent evaluations of bait quality by Henderson & Frampton (1999) and are presented below.

Specifications for carrot bait

Carrot supply: Carrots supplied will be:

- Royal Chantenay;
- harvested at a time when 90% of carrots weigh 100-200 g;
- clean-pulled within 4 days prior to requested date of delivery of the consignment;
- topped;
- free of carrot worm, stem rot, woody pith, mould, bruising, weed and weed seed, stones and other foreign objects;
- washed so that the consignment contains 99% carrot by weight.

Storage: On arrival at the airstrip carrots should be:

- covered by tarpaulins if there is a risk of overnight frosts;
- stored for no longer than is absolutely necessary. If delays occur because of weather then the period of storage will depend on temperature and humidity, but should not exceed 1 month in ideal weather conditions (i.e. low humidity, cool temperatures);
- free from signs of decay (heat, smell, or softness).

Palatability: The palatability of toxic bait should exceed 40% compared to recently manufactured non-toxic RS5 bait (6 g).

Efficacy: When 40 individually caged possums are presented paired trays containing 100 g of bait containing 0.15% 1080 and 100 g of non-toxic RS5 bait, at least 90% of possums shall eat a lethal amount of toxic bait. To ensure most animals are killed quickly and humanely, it is recommended that a minimum of 35 of 40 caged possums eat at least 8 g of bait (i.e. the amount of bait that administers 4 mg/kg of 1080 to a 3-kg possum).

Bait size and chaff:

- Carrot baits shall have a mean weight of 6 g and 95% of baits by weight shall weigh between 3 and 10 g.
- Chaff (pieces of carrot less than 0.5 g) shall make up less than 1.5% by weight of useable bait.
- Chaff as a by-product will make up less than 40% by weight of the pre-processed carrot.

Toxin: The 1080 used in baits shall be at least 93% pure sodium monofluoroacetate and contain less than 0.25% inorganic fluoride. The pH of a 0.1% aqueous solution of the 1080 powder shall be 6.5 or less. The 1080 stock solution will be 20% (±0.5%) sodium monofluoroacetate.

1080 concentration: Sodium monofluoroacetate will be surface-applied to carrot baits such that the concentration of 1080 in samples of 10 baits should be 1.5 ± 0.22 mg/g (i.e. all samples should have a concentration within 15% of the nominal concentration). The means of 10 or more such samples shall lie within ±5% of the nominal concentration. The concentration in 90% of 10 individual baits shall be within ±25% of the nominal concentration.

Colour: A green colour shall be incorporated into the bait to ensure it has a colour range of 221-267 by the New Zealand Standard Specification 7702 (section 23, Standards Act 1965). Surface colour shall be 98% or more of the surface area when tested by intercepts on a dot grid of 1 cm x 1 cm over a random sample of not less than 100 baits.

Masks: Food-grade cinnamon flavour (Bush, Boake and Allen, Auckland; Product No. 02-7780) shall be used to mask 1080 by mixing it into baits at 0.3% wt/wt. The lure mixture shall be made by adding 3 Lof flavour concentrate to approximately 16 L of soya bean or peanut oil, and applying 2 L of this mix per tonne of cut bait. Alternatively, 300 mL of cinnamon lure should be mixed in 700 mL of monopropylene glycol, and added to the spray tank containing 1080 solution at the rate of one litre per tonne of carrot. Cinnamon concentrations following bait preparation should never be less than 0.1% or more than 0.4% wt/wt.

Stability: If, because of storage, uncut carrots start to become soft or ferment, the carrots should not be used for manufacture of baits. Carrot baits may remain palatable for a week after manufacture (i.e. palatability to 20 individually caged possums will be >40%). The 1080 concentration in a sample of stored carrot bait should be within ±15% of the nominal concentration.

Leaching: Detoxification of carrot is reliant on biodegradation of 1080 by micro-organisms as baits rot, therefore intact baits must be analysed for traces of 1080 before livestock are introduced back into control areas.

Appendix 5. Protocol for achieving correct sowing rates using helicopter-underslung sowing buckets

Purpose: this protocol describes the Quality Assurance procedures required to calibrate the output of helicopter aerial sowing buckets, and to validate correct application rates.

Procedures:

A. Bucket calibration

1. Staff should wear protective glasses, overalls, and earmuffs.
2. Sow a swath of baits 300 m long in a paddock with short pasture while flying the helicopter at a flying speed of 50 knots and flying height 30 m above ground (i.e. normal operational use), and with the sowing bucket set for a moderate rate (e.g. approximately 5 kg/ha).
3. Record the swath width with a hip-chain at six randomly selected points along the swath and calculate the mean and standard deviation.
4. Use the following to calculate the required bucket output rate:

$$\text{Sowing rate (kg/ha)} = \frac{\text{Output rate (kg/min)} \times 324}{\text{Flying speed (knots)} \times \text{swath width (m)}}$$

5. Set the bucket securely on flat ground adjacent to the helicopter. Remove the spinner plate and place a tarpaulin underneath for bait collection. If removal cannot be achieved easily, place the tarpaulin (heavy grade) around the bottom of the sowing bucket to collect baits during operation.
6. Connect the bucket to the helicopter controls. Close the bucket opening.
7. Load the bucket with at least 100 kg of non-toxic pellets. These must be of the same mean size as the toxic bait to be used operationally.
8. Set the bucket-opening at a setting estimated to be approximately correct for the desired sowing rate.
9. If a tarpaulin is being used, check that the delivery section of the bucket is fully enclosed for safety. Start the bucket and activate the bucket opening while starting a timer.
10. Close the bucket opening after 15 seconds and stop the bucket.
11. Weigh the baits collected by the tarpaulin.

12. Repeat this method of sampling bucket output six times. Calculate the mean (and standard deviation) and multiply by four to convert to 'mean bucket output rate' in kg/min.
13. Vary the bucket opening and repeat until the desired mean output is achieved. Mark all settings on the opening mechanism and describe in operators' manuals.

B. Validation of sowing rate

14. Arrange the bucket opening at the setting found to deliver the correct output rate for the required application rate.
15. Sow a swath of baits at least 300 m long in a paddock with short pasture while flying the helicopter at a flying speed of 50 knots and flying height 30 m above ground (i.e. normal operational use).
16. Establish the boundaries of the swath and collect baits found along a randomly located, 1-m-wide belt-transect across the swath. Place bags in a plastic bag identified with the transect number. Also record the length of transect searched. Repeat six times. Random start points can be established by dividing the swath into segments 50 m long and randomly selecting a start point within each 50-m segment.
17. Weigh the baits collected from each transect and calculate the average weight per square metre and standard deviation. Convert to an application rate (kg/ha) for the entire swath.

Appendix 6. Protocol for assessing effectiveness of aerial baiting

Purpose: this protocol describes the Quality Assurance procedures required to assess the coverage and density of possum baits on the ground following aerial sowing.

Procedures:

1. The mean weight of bait is measured before aerial sowing by weighing a total of 200 baits randomly sampled out of at least four bags (i.e. 50 baits per bag).
2. Establish the start/finish coordinates and compass bearing for 10 parallel transects that lie perpendicular to the direction of flight paths. Transects should be located 200 m apart and traverse 1 km of the baited area.
3. Each transect requires two people for survey. One person navigates the transect marking it with hip chain, and indicating each 20-m increment by placing a plastic peg in the ground.
4. The second person searches 1 m either side of the transect for baits, recording the total number of baits found in each 20-m segment of the transect before removing plot pegs. Note, 'baits' are classified as particles weighing > 1g and smaller fragments are not recorded.
5. Where no baits are found in a 20-m plot, a search is conducted up to 25 m either side of the plot to determine if outlying baits are present. Presence or absence of such baits are recorded indicating a 'gap' in aerial baiting cover (i.e. in swaths of at least 50 m). **Coverage of aerial baiting** is then expressed as the percentage of plots that indicated gaps.
6. A graphical representation of the coverage can be created by constructing a diagram of bait coverage in which plots indicating gaps are linked between adjacent lines. Where gaps do not link obviously between lines, a small interruption in bait-flow is assumed and can be indicated by a small spherical gap centred on a single line. (Note: for an example see Fig. 6.1)
7. The **density of baits** on each plot is estimated as baits per hectare by multiplying the total counted by 250 (i.e. 10 000/40). An overall density for the surveyed area is then calculated by taking the mean value from individual plots.
8. The density of baits throughout the surveyed area is expressed as kilograms bait per hectare by multiplying the mean density of baits measured before aerial sowing (see 1). This can then be compared with the nominal sowing rate.

Appendix 7. Protocol for assessing bait size following aerial application.

Purpose: this protocol describes the Quality Assurance procedures required to assess the degree of bait-fragmentation occurring as a result of aerial sowing.

Procedures:

1. Describe the size-distribution of baits sampled before aerial sowing by randomly collecting a 1-kg sample of bait from each of five bags of bait as they are emptied. Samples should be collected by sweeping a container back and forth under the bag while it is slowly emptied, in order to collect pellets from different levels of the bag, including the base region.
2. Sieve each sample to separate out dust and small fragments weighing less than 0.5 g for carrot, and less than 1.0 g for cereal pellets. Weigh this component.
3. After sieving, weigh all baits individually. This is best done with an electronic balance interfaced to appropriate weight-classification software.
4. Determine the proportion of the sample by both weight and number of baits that fall into weight increments of 1 g, commencing at 0.5 g (i.e. 1.0-1.9, 2.0-2.9, 3.0-3.9 g etc.) for carrot and 1.0 g for pellet bait. Plot the frequency distribution of mean weight (and number) baits in each class and standard deviations.
5. Calculate the overall mean weight (pre) of bait.
6. Describe the degree of fragmentation of bait before aerial sowing using the mean proportion of the sample by weight less than 0.5 g (for carrot bait) or less than 1 g for cereal pellet. (To meet standard bait specifications, this should not exceed 1.5% for carrot bait and 5% for cereal pellet bait).
7. After aerial sowing, collect all baits along a 1-m-wide belt-transect except fragments likely to weigh less than 0.5 g (carrot) or 1.0 g (cereal pellet). The transect should be orientated perpendicular to the direction of flight paths, and should extend until five samples of approximately 1 kg have been collected. Samples must be handled carefully to avoid fragmentation.
8. For each sample weigh all baits, classify in weight classes as above (4), plot frequency distributions as above (4), and calculate the overall (post) mean weight of bait.
9. Describe the degree of fragmentation caused by aerial application as:

$$\text{i) Reduction in bait weight} = \frac{\text{Mean weight (pre)} - \text{Mean weight (post)}}{\text{Mean weight (pre)}} \times 100$$

and

$$\text{ii) Proportional increase in fragments} = \frac{\text{Proportion (pre)} - \text{Proportion (post)}}{\text{Proportion (pre)}} \times 100$$